DESIGN AND MANUFACTURING OF COMPOSITE STRUCTURES USING THE RESIN TRANSFER MOLDING TECHNIQUE

by

Casey Keulen

B.Eng., University of Victoria, 2006

A Thesis Submitted in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Mechanical Engineering

DESIGN AND MANUFACTURING OF COMPOSITE STRUCTURES USING THE RESIN TRANSFER MOLDING TECHNIQUE

By

Casey Keulen

B.Eng., University of Victoria, 2006

Supervisory Committee

Dr. Afzal Suleman, Supervisor (Department of Mechanical Engineering, University of Victoria)

Dr. Mehmet Yildiz, Supervisor (Department of Mechanical Engineering, Sabanci University)

Dr. Nikolai Dechev, Departmental Member, (Department of Mechanical Engineering, University of Victoria)

Dr. Venkatesh Srinivasan, Outside Member, (Department of Computer Science, University of Victoria)

Supervisory Committee

Dr. Afzal Suleman, Supervisor (Department of Mechanical Engineering, University of Victoria)

Dr. Mehmet Yildiz, Supervisor (Department of Mechanical Engineering, Sabanci University)

Dr. Nikolai Dechev, Departmental Member, (Department of Mechanical Engineering, University of Victoria)

Dr. Venkatesh Srinivasan, Outside Member, (Department of Computer Science, University of Victoria)

ABSTRACT

Composite materials have the potential to revolutionize life in the 21st century. They are contributing significantly to developments in aerospace, hydrogen fuel cells, electronics and space exploration today. While a number of composite material processing methods exist, resin transfer molding (RTM) has the potential of becoming the dominant low-cost process for the fabrication of large, high-performance products [1]. RTM has many advantages over alternative processes, including the capability of producing complex 3D shapes with a good surface finish, the incorporation of cores and inserts, a tight control over fiber placement and resin volume fraction and the possibility of embedding sensors into manufactured components for structural health monitoring. Part of the reason RTM has not received widespread use is due to its drawbacks such as its relatively trial and error nature, race tracking, washout, high cycle time and void formation. The basic operation of the process involves loading a fiber reinforcement preform into a mold cavity, closing the mold, injecting resin into the mold and allowing the resin to cure. To study the resin transfer molding process and issues affecting it, a laboratory containing an experimental RTM apparatus has been established. The apparatus has a glass window to observe the mold filling process and can incorporate various mold shapes such as a quasi-2D panel, a 3-D rectangular section and a 3-D semicircular section. To characterize the flow through the molds a commercial CFD software has been used. This thesis describes the establishment of this laboratory and preliminary studies that have been conducted.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Latin Letters

Symbol	Description
k	permeability
d	channel width
h	cavity thickness
l	width of area sub-region
k_y	permeability in transverse direction
p_c	capillary pressure
V_f	fiber volume fraction
r	flow channel radius
R	characteristic fiber radius
V_a'	empirical parameter
k'	empirical parameter
C	fiber shape factor
K_{perp}	permeability perpendicular to fibers
K_{par}	permeability parallel to fibers
u, u_x	velocity in x direction
v	velocity in y direction
w	velocity in y direction
k_{ij}	permeability tensor
V_v	volume of void space
V_T	total volume
C	color field
t	time
$\vec{U}$	true velocity
A	area porosity
$\overline{\overline{R}}$	resistance to flow
g	gravity
p	pressure
$\overline{\overline{K}}$	permeability tensor
$\vec{V}$	velocity vector

Greek Letters

Symbol	**Description**
γ	resin surface tension
θ	contact angle between fiber and flow
μ_e	effective viscosity
μ	viscosity
μ_{air}	viscosity of air
$\mu_{re\sin}$	viscosity of resin
β	amount of slip
τ_{xy}	shear stress
ρ	fluid density
η	dynamic viscosity
ϕ	porosity

Acronyms

Symbol	**Description**
CFD	computational fluid dynamics
RTM	resin transfer molding
3D	three dimensional
2D	two dimensional
PMC	polymer matrix composite
CNC	computer numeric control
OMC	organic matrix composite
CMC	ceramic matrix composite
MMC	metal matrix composite
HCM	hybrid composite material
PVC	polyvinylchloride
PAN	polyacrylonitrile
PPD-T	poly para-phenyleneterephthalamide
SRIM	structural reaction injection molding
VARI	vacuum assisted resin injection
VARTM	vacuum assisted resin transfer molding
SCRIMP	Seeman Composite Resin Infusion Molding Process
DAQ	data acquisition system
FDM	finite difference method
BEM	boundary element method
FEM	finite element method
CV/FEM	control volume/finite element method
SPH	smoothed particle hydrodynamics
VOF	volume of fluid
CV	control volume

ACKNOWLEDGEMENT

I would like to take this opportunity to express my appreciation to those who helped me complete this thesis.

First of all, I owe many thanks to my supervisors, Dr. Afzal Suleman and Dr. Mehmet Yildiz for their guidance, advice and support. Their constant supervision and input made this work possible.

I would like to thank all my professors, colleagues and office mates for the encouragement during the period of my study.

To Dr. Steve Ferguson who gave input on design and helped fabricate a portion of the experimental apparatus.

Special thanks to my parents, my girlfriend and friends outside of school who gave me support and a chance to get away from my studies when I needed to.

DEDICATION

To my mother and father who will be with me always.

Chapter 1 INTRODUCTION

1.1 Introduction

A composite material is defined as a material composed of two or more constituent materials that remain separate and distinct on a macroscopic level. Composite materials or 'composites' are found everywhere from surfboards and golf clubs to airplanes and space shuttles and are becoming a very important part of life in the 21st century. Recently the price of composites has reached the point where, in some cases they are more cost effective than traditional materials. One reference states that there is an estimated 100-1000 Euros of savings per kilogram reduced in aircraft travel, this opens the doors for potential composite applications as can be seen by the wide use in the new Boeing and Airbus aircraft [2].

Generally speaking composite materials or 'composites' can be broken into two parts, the matrix and the reinforcement. The reinforcement supplies the strength and stiffness while the matrix binds the reinforcement and provides a means of transferring the load throughout the reinforcement. A synergism between the constituents produces material properties unavailable from the individual materials. A wide variety of constituent materials are used in composites such as plastic, metal and ceramic for the matrix and carbon, aramid, glass, boron or metal for the reinforcement. A common class of composites is polymer matrix composites (PMC) where the matrix material is a polymer and the reinforcement is generally made up of fibers. Typically a composite material and a composite part are made at the same time as opposed to more conventional materials where the material is first produced in a raw form then machined or worked into the final shape. In its most basic form, producing a fiber reinforced polymer matrix composite part involves placing the fibers in a desired shape and saturating them with the matrix or positioning pre-saturated fibers in a desired shape. Closed molds, one-sided molds and plugs are the most common methods of attaining the desired shape of a composite part.

The manufacturing method of focus in this thesis is resin transfer molding (RTM). It was chosen as the area of interest due to the relatively unexplored potential in producing complex geometry, high performance aerospace components and the many aspects that require study. There is a lot of room for development in this field and the possibility of incorporating emerging technologies such as fiber optic sensors, process monitoring, structural health monitoring and smart structures.

Resin transfer molding is a subcategory of liquid composite molding that involves the use of a closed mold to produce a near net shape part. The mold is loaded with preformed fiber reinforcement then closed. The matrix material, commonly referred to as resin is injected into the mold, saturating the fiber. The mold is maintained at a prescribed temperature/time cycle until the molded part is fully cured and ready to be removed. Figure 1-1 shows a schematic of the RTM process and the apparatus used in subsequent experimentation.

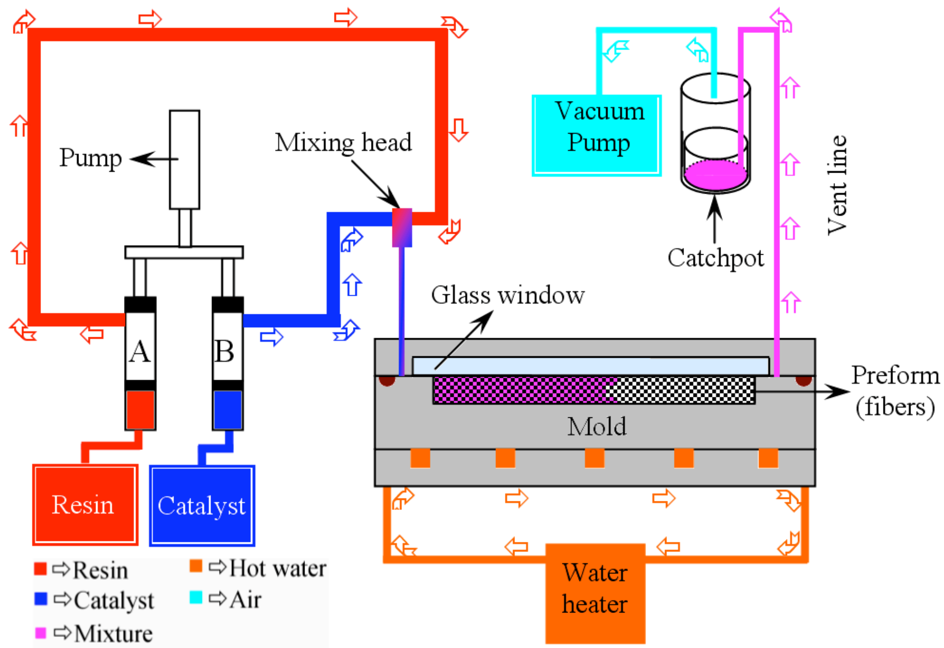

Figure 1-1: Schematic of RTM apparatus (for this research, pressure pot is used as an injection system)

Although it has been around for some time, RTM is still a maturing technique that requires research and development. One major issue is mold filling and the effect this has on the entire process. If a prediction of the resin flow can be made prior to manufacturing the mold, a fully functional mold can be designed and produced without the guesswork and luck currently required. A prediction of the flow is indispensable when complex 3-D geometries are involved. Parametric studies can also be done to optimize the process to improve efficiency and reduce costs. Sensors may be embedded in a composite component and used to monitor resin flow, cure, and structural health of composite components while embedded actuators can be used to control physical characteristics such as shape, flexibility and damping.

1.2 Background

Composite materials are probably the oldest classification of materials dating back to straw and clay bricks documented in ancient Egyptian tomb paintings currently held at the Metropolitan Museum of Art in New York City. Polyester/glass fiber composites as we know them have been around since the Second World War. As early as 1942 Owens-Corning was producing composite aircraft parts for the war. Boron fiber was introduced in the 1960's and carbon fiber in the 1970's [3]. Advanced (fiber reinforced polymer matrix) composite materials can be defined as composite materials that use continuous fibers that are sufficiently long that any increase in their length will have no effect on the mechanical properties of the material, this is in contrast to composite materials that are made of short discontinuous fibers where an increase in fiber length corresponds to an increase in material properties. Since their inception, these advanced composite materials have made their way into many critical applications where strength, weight and stiffness are critical.

The raw materials used to produce fiber-reinforced composites are available in a number of forms. A wide variety of fiber forms are available such a chopped fiber, continuous single strand fiber, bundled fibers (often called tows), fiber rope and fiber tape or cloth. The matrix is generally a thermoset plastic that is a two part liquid that is mixed at a specific ratio prior to use to induce cross-linking (hardening). Another form of raw composite material is called pre-impregnated material or 'prepreg' which is a reinforcement that comes saturated with the matrix and is generally in cloth form. Prepreg material is held at an elevated temperature to cure and is usually done with an autoclave oven.

There are currently numerous techniques used to produce composite parts. Common techniques include hand lay-up/spray-up, filament winding, pultrusion, automated fiber placement and liquid composite molding such as resin transfer molding (RTM).

Hand lay-up/spray-up involves an operator that manually lays out the fibers and saturates them with resin or sprays both resin and fiber onto a mold with a spray gun. This technique is very labor intensive and the fiber placement and quality of the produced part is not repeatable and depends heavily on the operator's skill. This method puts the operator in direct contact with dangerous airborne chemicals requiring specialized safety equipment and introduces the possibility of serious health repercussions.

Filament winding is an automated process in which resin saturated continuous fibers are wound around a mandrel to produce the desired part. Since the parts are wound this process has limitations on the shapes that may be produced and generally only conducive to axi-symmetric parts such as pressure vessels or pipes. Due to the placement of the fiber bending and torsional loading is not desirable to parts made with this technique.

Pulltrusion is similar to conventional extrusion and involves pulling fibers through a die to create a desired shape. This technique is only applicable to constant cross-section extruded shapes such as I-beams or bars. The fiber orientation is also limited, as the fibers must run along the length of the part. Parts produced with this method are not sensitive to bending and torsion like filament wound parts are, however due to the orientation of the fibers internal pressures are not desirable ruling out the possibility of producing high pressure pipes with this technique.

Automated fiber placement involves a large CNC gantry that rolls prepreg fiber cloth onto a one sided mold. This technique has the advantage of controlling the application pressure however only one side of the part has a quality surface finish. Since prepreg cloth is used the part must be heated to cure the resin.

Depending on the type of resin used, most of the aforementioned processing techniques require the use of an autoclave oven to cure and/or post-cure the resin. For larger parts this requires a large autoclave and the complicated logistics of moving a mold in and out of the autoclave. One benefit of using an autoclave is that pressures of 5 atm. can be reached which can create higher quality parts than many alternative techniques.

RTM has the advantage over other types of manufacturing methods because it can produce complex 3D parts with a quality surface finish and tight tolerances as opposed to quasi-2D parts with only one quality surface, loose tolerances and low repeatability. RTM also allows for precise fiber placement and the inclusion of cores and inserts. Parts produced with this technique are very repeatable and do not rely on operator skill. The whole molding procedure can be done automatically and since the process is closed mold the operator’s exposure to hazardous chemicals is minimal. These qualities make RTM an attractive technique for producing high-end composite components for aerospace and other applications that demand high quality, repeatable components.

The first documented application of RTM appears to be from a US navy contract for the development of 28ft long personnel boats. This contract from 1946 specified the use of glass fiber and polyester resin to be molded using a vacuum injection method. For this method the reinforcement was held between two mold halves and the resin poured into a trough in which the lower edge of the tool sat. The resin was then drawn up by vacuum placed around the top of the tool. While this method worked satisfactorily for the Navy's purposes it was very problematic and unsuitable for complex geometries related to aerospace applications [4].

The early history of RTM for aerospace can be traced back to a series of six patents placed in the 1950's by Harold John Pollard and John Rees of Bristol Aircraft Limited. By 1956 nearly all the features for RTM of aerospace applications had been introduced. In February of 1955 a patent that describes the process as we know it today was applied for. The applications quoted in the patent were aircraft fuselages and automobile bodies (at the time Bristol Aircraft Limited was a part of the same group as the Bristol Car Company). In October of 1955 a patent for an injection mechanism that mixes two part resins in a controllable way prior to injection with an integrated solvent flush for the mixing cavities and injection lines was applied for. Today this is still the most common, user friendly and economical method of injection [4].

1.3 Motivation

Many aspects of RTM can be studied such as the resin flow, fiber deformation during injection, the interaction of macroscopic and microscopic flow fronts, heat transfer between the matrix, reinforcement and mold during injection, resin cure dynamics, process monitoring and control and overall cycle time. All of these aspects can be studied and benchmarked with an adequate laboratory scale experimental setup.

The motivation behind this thesis is to establish an advanced composite materials research laboratory with the capability of manufacturing polymer based composite materials with the RTM method. Therefore, a laboratory scale resin transfer molding system was designed and built. The developed RTM apparatus can also be used to study the flow of resin through the fiber during injection. The present research also attempts to study the mold filling process with a multipurpose fluid dynamics (CFD) software package. Therefore, the developed RTM apparatus can be used to measure permeability which is an input parameter for modeling and can be used to validate modeling studies of the mold filling process.

If an accurate model of resin flow can be devised it can be used to validate a mold design prior to manufacturing the mold. Typically molds are designed based on trial and error methods and may have problems adequately filling the mold rendering an expensive mold useless. A parametric study may also be done using a fluid flow model. This study could optimize the process resulting in smaller turn around times, less material waste and higher quality parts.

Typical issues associated with the fluid flow are dry spots due to converging flow fronts that occur because of part geometry, edge effects or 'race tracking' where the resin takes a preferential path between the edge of the mold and the fiber reinforcement, interaction of micro and macroscopic flow resulting in small air bubbles that become trapped within fibers and improper inlet/outlet placement resulting in excessive filling times or incomplete filling.

When the resin flows around an obstacle for example an insert placed in the mold the flow front is broken into two separate flow fronts that both progress at different rates. When these two flow fronts meet one will be more advanced than the other allowing for the possibility of air pockets becoming trapped. If the advancement of the flow fronts can be accurately predicted then the mold can be designed accordingly to eliminate this problem.

Race tracking is a significant issue with RTM that can easily ruin a component or possibly render a mold useless. When fiber reinforcement is placed in the mold there will inevitably be a region of lower fiber volume fraction and permeability where the fibers meet the edge of the mold. This creates a channel with less resistance resulting in a preferential flow path. If the resistance to flow is low enough the fluid will not flow through the fibers and instead flow through these paths, possibly never saturating the mold.

Most woven cloth is composed of tows (bundles of individual fiber strands) that are arranged in a criss-cross pattern. To fully saturate the cloth the fluid must flow both between the tows and the individual fiber strands, referred to as macroscopic and microscopic flow respectively. If the average fluid flow is too fast the microscopic flow will lag behind the macroscopic flow creating two different flow fronts, which upon meeting will create tiny voids within the tows.

To characterize these different phenomenons, a laboratory scale resin transfer molding (RTM) system must be employed. The system should have a transparent viewing window so that the fluid flow can be monitored during the process. Pressure sensors at the inlet and outlet locations must be installed to determine the pressure differential across the mold and pressure sensors throughout the mold to obtain data that can be compared to a computational model. To make the system practical and capable of using different types of resin, the mold must be rigid to maintain its shape under pressure, contain a heating/cooling system to cure the resin according to required temperature-time schedules, safe and easy to operate with one person and versatile so that different mold shapes may be interchanged.

1.4 Scope of Thesis

As mentioned there are many different areas of RTM that can be studied. The objectives of this thesis are to design and implement a laboratory scale mold for both quasi-two and three-dimensional shapes and attempt to characterize macroscopic fluid flow during the filling process with a commercially available computational fluid dynamics (CFD) software suite.

The design and implementation challenges, operation methods, and challenges of operating the experimental system will be discussed in detail. A description of the CFD fluid flow model, the techniques used to characterize certain flow phenomenon and the methods used by the code to solve the problem will be covered. Possible future work that can be done with the system will also be discussed.

1.5 Structure of the Thesis

The first chapter briefly describes the background of the thesis and composite materials, why the work was done and the objectives of the project. Chapter 2 gives a more detailed background of composite materials including information related to the issues that are studied. Chapter 3 describes the setup of the laboratory and the design and manufacture of the experimental apparatus. Chapter 4 describes the computational CFD model used to predict the flow of resin and how it is implemented. Chapter 5 states the results of this work and Chapter 6 states the conclusions and future work of this project.

Chapter 2 COMPOSITE MATERIALS

2.1 Introduction

A composite material is an engineered material that is made of two or more constituent materials that remain separate and distinct on a macroscopic level while forming a single component. In general, composite materials have a continuous matrix phase which binds a stronger, stiffer reinforcement phase [7]. The matrix binds and protects the reinforcement and gives the part form, while the reinforcement provides desired structural and physical properties, for example stiffness or electrical conductivity. Examples of common day products made out of composite materials are fishing rods, golf clubs (with fiber glass or carbon fiber reinforcements), pickup truck canopies, sinks, bathtubs, hot tubs, skis, surfboards, electrical enclosures and circuit boards.

Composites can be tailored to produce desirable structural, electrical, thermal, tribological and environmental resistance properties. Desired properties can be achieved by constituent material selection, constituent material arrangement and manufacturing processes. In some cases composites are more cost effective due to their specific properties and the fact that large components may be produced in one piece eliminating assembly time and cost. The focus of this thesis is on polymer matrix composites (PMCs) with fibrous reinforcement and resin transfer molding. For the sake of completeness, an overview of all types of composites will be included;

2.2 Classes of Composite Materials

Two levels of classification exist for composite materials. They can be classified according to the matrix type and reinforcement form.

Generally speaking there are three types of matrices: organic matrix composites (OMCs), metal matrix composites (MMCs) and ceramic matrix composites (CMCs). OMCs include polymer matrix composites (PMCs) and carbon matrix composites (CMCs). The matrix material makes up the majority of the appearance, dictates the manufacturing process and range of applications. This thesis focuses on processing of PMC's, detailed information on other types of composites is beyond the scope of this thesis and will not be included.

There are a variety of forms of reinforcement. These include particulate reinforcements, wisker reinforcement, continuous fiber laminated composites and woven composites. A reinforcement can be classified as a particle if all dimensions are roughly equal such as spheres, rods and flakes. Whiskers generally have an aspect ratio between 20 and 100 and are classified with particulates when used in MMCs. These types of reinforcement are classified as discontinuous. Continuous fiber reinforcements have lengths much greater than their widths. Continuous and woven fiber reinforcements fall into these categories. A reinforcement can be classified as continuous when an increase in length does not effect the properties of the composite material and can be referred to as an advanced composite. This is not the case with discontinuous fibers where the fiber length has a substantial impact on final properties of the composite material.

A relatively new type of composite material is hybrid composites. A hybrid composite is defined as a composite that consists of more than one reinforcement phase, either multiple reinforcement materials or reinforcement forms. For example [5] investigates the use of woven glass fiber with a combination of chopped carbon fibers. Another class of composites worth mentioning is nanocomposites. These composites generally use carbon nanoparticles. There is a great deal of interest and research in this field however there is yet to be a notable commercial application.

2.3 Advantages and Disadvantages of Composites

2.3.1 Advantages

The advantages of composites generally depend on the type of composite, PMC, MMC or CMC. PMCs generally have much better specific properties than competing materials while MMCs generally have better strength and wear properties and CMCs have excellent high temperature properties. However there are many exceptions to these rules. One common advantage that composites have over traditional materials is that they are tailorable to the specific application; a virtually limitless combination of properties can be produced with the limit depending on the designer's imagination.

The advantages of PMC are generally found in their specific properties, commonly specific strength and specific stiffness. Depending on the application these properties translate into reduced operating costs, especially in aerospace applications. PMCs also have excellent damping characteristics which can translate into a more comfortable aircraft cabin due to reduced noise; when playing with composite sporting equipment this results in reduced fatigue and pain. PMCs are not affected by corrosion, which makes them great candidates for marine and outdoor applications. In larger components PMCs can be used to fabricate an entire component as one piece, which reduces the manufacturing costs associated with assembly time. The electrical properties of PMCs can be controlled quite accurately. Both high electrical conduction and insulation are possible. More recently PMCs have bought their way into new applications due to a reduction in their price.

Originally, the motivation behind the development of MMCs was to improve the strength of metallic materials while maintaining their desirable properties such as chemical inertness, shear strength and high temperature performance. Some types of MMCs, specifically particulate MMCs have a price and processing advantage over traditional metallic materials with similar properties. Some MMC's are capable of producing a combination of properties otherwise not available, for example a combination of high wear resistance and excellent electrical conduction is obtained by infusing porous tungsten with silver to be used in electrical contacts. In general MMCs have an advantage over PMCs due to higher tensile strength and shear modulus, higher melting point, lower coefficient of expansion, resistance to moisture and higher ductility.

The major advantage that CMCs have over other materials is their extremely high operating temperature, in some cases above 1650 °C. CMCs also have an advantage over super alloys by having up to 70% lower density. With adequate research and development CMCs have the potential, when used in advanced engines to increase the operating temperature and eliminate the need for cooling fluids.

2.3.2 Disadvantages

Despite the numerous advantages that composite materials posses there are still disadvantages that keep them out of many applications.

The cost of constituent materials is fairly high (although it has come down substantially in the last few decades). The cost of fabrication can also be high depending on the desired properties and quantity of components. The expertise required to work with composites is greater than that required to work with commonly used metals and in many cases not available. Additional safety equipment and training adds to the cost.

Most composite materials have inherent problems with fastening to other parts. Holes cannot be effectively tapped into most composites due both to the constituent materials and the fact that most composite parts are quite thin. This requires metallic inserts which act as stress risers and have interface issues. Composite parts are commonly bonded to other parts. Care must be done when selecting an adhesive and area to bond because the bond may act as a stress riser.

Since most composite materials are non-isotropic, traditional strength of materials theory cannot be used to predict failure along with the fact that other modes of failure may occur. It is also difficult to predict the material properties since they are dependent on the constituent materials, matrix form and processing technique.

Post processing of composites is not trivial. Due to the properties of certain materials composites may be very difficult to cut and drill rendering traditional techniques useless. Cutting tools must be sharpened and replaced more often that those used on traditional materials. Cutting and drilling certain composites can produce very fine particles. When inhaled, these fine particles may remain in ones body for the remainder of their lifetime .

Repairing composite materials is more of an art than a science. Due to the vast variety of constituent materials used, a priori knowledge of the composite part to be repaired is essential and techniques vary depending on materials used and construction technique.

Most PMCs suffer from poor toughness and impact damage. PMCs are also affected by UV rays emitted from the sun and tend to degrade over time unless properly prepared.

2.3.3 Hybrid Composite Materials

Hybrid composite materials (HCMs) are defined as integrated dissimilar materials, one or more being a composite. In a way, these materials are composites comprised of composites. This could include the combination of a traditional composite such as glass fiber/epoxy with aluminum or another metal or a combination of two or more reinforcements such as glass fiber and carbon fiber. The field of HCMs is still emerging and requires development to become more commercially viable.

There are a number of reasons to use HMCs. By combining two or more materials one can obtain the beneficial properties of both while reducing their undesired properties. By using a lower cost/strength material in the main part of the body such as glass fiber and a higher cost/strength material such as carbon fiber in areas of high stress, a designer can create a component that will meet the desired strength properties yet reduce cost. Some combinations of materials can create unusual anisotropic properties. For example thermal management can be achieved by using a combination of refractive material and a material with high thermal conductivity; when layered this combination can conduct and disperse heat over the area of the component while little heat is conducted through the thickness of the material.

Hybrid reinforcement is commercially available in the form of woven fabrics. For example, carbon and aramid can be combined in a fabric to create a reinforcement material with high impact resistance and high compressive and tensile strength. Aramid and glass are combined to produce a lower cost material with good compressive and tensile strength. Carbon and glass are combined to obtain a lower cost, lower density reinforcement with high tensile and compressive strength and high stiffness. A hybrid of aramid reinforced aluminum laminate is commercially used as secondary structural components on fixed-wing subsonic aircraft.

2.4 Fiber Reinforcement

Fiber reinforcement is the most common type of reinforcement material used in PMCs and other types of composites. Each fiber is specific to the matrix type, for example a glass fiber reinforcement made for use with PMCs cannot be used with MMCs or CMCs. This is generally due to the operating temperatures of the reinforcement as well as the sizing (coating) on the fiber used to enhance bonding and saturation.

Fiber reinforcement comes in a variety of materials and forms. The most common materials used as fiber reinforcement for PMCs are glass, carbon, aramid and boron. These materials are available in such forms as chopped fibers, strand mats, woven fabrics, multiaxial layers, roving and rope. In most cases the desired properties of reinforcements are specific strength and specific modulus. As well, the reinforcement must be strong, stiff and lightweight. Table 2-1 gives a comparative overview of the qualitative properties of aramid, carbon and glass fibers. Table 2-2 gives some properties of selected fibers.

Table 2-1: Comparison of qualitative fiber properties [6]

Property	Aramid	Carbon	Glass
High Tensile Strength	Fair	Excellent	Fair
High Tensile Modulus	Fair	Excellent	Poor
High Compressive Strength	Poor	Excellent	Fair
High Compressive Modulus	Fair	Excellent	Poor
High Flexural Strength	Poor	Excellent	Fair
High Flexural Modulus	Fair	Excellent	Fair
High Impact Strength	Excellent	Poor	Fair
High Interlaminar Shear Strength	Fair	Excellent	Excellent
High In-plane Shear Strength	Fair	Excellent	Excellent
Low Density	Excellent	Fair	Poor
High Fatigue Resistance	Fair	Excellent	Poor
High Fire Resistance	Excellent	Poor	Excellent
High Thermal Insulation	Excellent	Poor	Fair
High Electrical Insulation	Fair	Poor	Excellent
Low Thermal Expansion	Excellent	Excellent	Excellent
Low Cost	Poor	Poor	Excellent

Table 2-2: Quantitative fiber properties [7]

Fiber	Typical Diameter (μm)	Specific Gravity	Tensile Modulus (GPa)	Tensile Strength (GPa)	Strain to Failure (%)	Coefficient of Thermal Expansion (10^{-6}/°C)	Poison Ratio
Glass:							
E-glass	10	2.54	72.4	3.45	4.8	5.00	0.2
S-glass	10	2.49	86.9	4.30	5	2.90	0.22
PAN Carbon:							
T-300	7	1.76	231	3.65	1.4	-0.60	0.2
AS-1	8	1.80	228	3.10	1.32	-	-
AS-4	7	1.80	248	4.07	1.65	-	-
T-40	5.1	1.81	290	5.65	1.8	-0.75	-
IM-7	5	1.78	301	5.31	1.81	-	-
HMS-4	8	1.80	345	2.48	0.7	-	-
GY-70	8.4	1.96	483	1.52	0.38	-	-
Pitch Carbon:							
P-55	10	2.00	380	1.90	0.5	-1.30	-
P-100	10	2.15	758	2.41	0.32	-1.45	-
Aramid:							
Kevlar 49™	11.9	1.45	131	3.62	2.8	-2.00	0.35
Kevlar 149™	-	1.47	179	3.45	1.9	-	-
Technora™	-	1.39	70	3.00	4.4	-6.00	-

2.4.1 Glass Fiber Reinforcement

Glass fibers are the most commonly used and most versatile fiber reinforcement in the industry today. Due to their price, glass fibers are found in structural components, sporting goods, printed circuit boards and common household items like bathtubs and sinks. The chemical composition of glass fibers is very similar to everyday soda-lime glass used to make windows and jars and consists mainly of silica (SiO_2) however other oxides such as Al_2O_3, B_2O_3, CaO and MgO are added to enhance physical properties and processability.

There are generally two categories of glass fibers, inexpensive general-purpose and premium, special-purpose fibers. General-purpose glass fibers are designated E-glass (see Table 2-3 for designation explanation) and are used in over 90% of glass fiber applications [7]. Fibers are classified by properties and designated with a letter. Many of these types of fibers are subjected to ASTM specifications for composition and properties. Some examples are given in Table 2-3.

Table 2-3: Glass Fiber Designations

Designation	Property or Characteristic
E, electrical	low electrical conductivity
S, strength	high strength
C, chemical	high chemical durability
M, modulus	high stiffness
A, alkali	high alkali or soda lime glass
D, dielectric	low dielectric constant

Glass fibers are produced by forcing molten glass through a platinum-rhodium bushing that has the desired diameter. Glass is an amorphous solid that is created by rapidly cooling the molten material once it is drawn through the bushing before crystals have a chance to form. Once formed into fibers a coating called *sizing* is applied by passing the fibers through a bath of liquid sizing. Sizing helps to protect the fibers from each other since they are very abrasive without it. It also improves fiber handling and bonding to resin. The type of sizing and chemical composition of glass determines the classification of fiber. Once formed individual fibers are processed into a variety of forms ranging from single strand to woven mat, various forms are discussed later in the chapter.

The average tensile strength of glass fibers exceeds 3.45 GPa, however handling of the fibers during packaging and processing produces surface damage, which reduces the tensile strength to the range of 1.72-2.07 GPa [8]. These surface flaws continue to reduce the strength of the fibers when subjected to a cyclic load. The presence of water also reduces the tensile strength since it bleaches out alkalis from the surface deepening the flaws.

2.4.2 Carbon Fiber Reinforcement

Carbon fiber, originally developed for and used in aerospace applications because of its high specific strength and stiffness is finding its way into a wide variety of alternative applications due to the significant drop in cost. This year the global market for carbon fiber has grown over 12% and is expected to reach 50 million lbs by year 2010 [1]. The price of carbon fiber is expected to reach $5/lb in 2008, a significant reduction from $150/lb in 1970 [1].

As quoted in [7] “Composites made from carbon fiber are five times stronger than grade 1020 steel for structural parts, yet are still five times lighter. In comparison to 6061 aluminum, carbon fiber composites are seven times stronger and two times stiffer, yet 1.5 times lighter. Carbon fiber composites have fatigue properties superior to all known metals and when coupled with the proper resins, carbon fiber composites are one of the most corrosion resistant materials available”. Carbon fibers can conduct electricity and are used to dissipate static electricity in electronic devices, a property that glass fibers do not posses.

There are three common precursor materials used to produce carbon fiber: PAN (polyacrylonitrile), pitch and rayon. The type of precursor material and manufacturing method plays an important role in the properties of the fiber. PAN is the most common precursor material and generally produces the highest tensile and compressive strength and strain at failure of the three types. Pitch fibers are the second most common and have very high modulus values compared to PAN fibers, however have a lower tensile strength. Fibers produced from rayon are the least common.

Carbon fibers are generally classified into three types: standard modulus, intermediate modulus and high modulus however there are other fibers available that fall in between these classifications.

Carbon fibers have a negative coefficient of thermal expansion. By exploiting this property, engineers have been able to produce composites that have a coefficient of thermal expansion of zero over a limited temperature range by using appropriate matrix materials.

The specifics of producing carbon fibers depend on the type of precursor material used although the general process is quite similar. PAN is a form of acrylic fiber and is manufactured by spinning the PAN polymer into filament. The filament is then manipulated into the desired fiber size, stabilized by heating to 200-300 °C in an oxygen rich environment and carbonized by heating the fibers to 1000-1500 °C in a carbon rich environment. The fibers are then surface treated and coated with a sizing. Pitch is a mixture of aromatic hydrocarbons and is made from petroleum, coal, tar, asphalt or PVC [7]. The pitch is heated above 300 °C to polymerize the aromatic rings and produce a mesophase, which is a disk like liquid crystal phase. Filaments are produced by melt spinning the mesophase through a spinneret. Once the filaments are produced the remainder of the process is similar to that of PAN fiber.

There are generally three sectors where carbon fiber is used; these are aerospace, sporting goods and industrial/commercial applications. Growth is the fastest in the industrial/commercial sector as engineers become more competent with carbon fiber, realize its potential and the cost comes decreases. While generally more expensive as a direct replacement of a metal part, in certain situations carbon fiber reinforced composite parts have proven more economical in the long run due to reduced maintenance, faster processing speeds and improved reliability. Applications such as carbon fiber drive shafts that are corrosion resistant, lightweight, and have high stiffness are taking the place of traditional steel shafts. The oil and gas industry is starting to use carbon fiber for pipelines due to its fatigue resistance and for mooring deep-water oil platforms. Carbon fiber "wallpaper" has been used extensively in Japan to seismically retrofit bridges. Carbon fiber is ideal for aerospace applications because of its specific strength and stiffness and its invulnerability to fatigue failure. In the aerospace industry, weight savings are generally more important than cost savings. Some notable aerospace applications of carbon fiber are the Boeing 787 "Dreamliner" which is the first commercial aircraft to use a composite structure rather than metal and the Airbus 380 which will use carbon fiber for the entire wing structure. Carbon fiber has made its way into the sporting sector through its use as golf clubs, fishing rods, hockey sticks, tennis racquets, bicycle frames and skis.

2.4.3 Aramid Fiber Reinforcement

DuPont was the first to make aramid fibers commercially available in the 1970's. All aramid fibers are proprietary formulations and produced by companies such as DuPont in USA, Teijin and Unitika in Japan and Akzo-Enka in the Netherlands and Germany. One of the most common forms is Kevlar by DuPont.

Aramid fibers have the lowest specific gravity and specific tensile strength of commonly available fibers. They are about 40% lighter than glass and about 20% lighter than carbon [8]. Aramid exhibits high toughness making it ideal for ballistic armor, tires and asbestos replacement in brakes and clutches. One common application is in bulletproof vests worn by police officers and military personnel. Aramid fibers are ductile in compression and bending with considerable energy absorption and exhibit a high degree of yielding in compression, a property not common to carbon or glass. Like carbon fibers, aramid fibers have a negative coefficient of thermal expansion; this property is used to produce low thermal expansion printed circuit boards. Also like carbon fibers aramid fibers have excellent fatigue resistance. Aramid fibers possess good electrical insulation properties and chemical resistance.

The compressive strength of aramid fiber is only about 20% of its tensile strength making it a poor choice for structural applications under compression [8]. Aramid fibers are difficult to cut and machine due to their high strength. They are also more expensive and not as readily available as other forms of reinforcement.

Aramid fibers are based on rod-like polymer chains comprised of para-linked aromatic amides. The chemical composition of Kevlar is poly para-phenyleneterephthalamide (PPD-T) and is made from a condensation reaction of paraphenylene diamine and terephthaloyl choride. These fibers are known as liquid crystalline polymers and are manufactured by extruding a PPD-T solution through a spinneret. When forced through the spinneret the liquid crystalline domains orient in the fiber axis (or flow) direction, which contributes to the high properties of these fibers. Each manufacturer uses a different chemical composition and specific manufacturing process for each type of aramid fiber.

2.4.4 Fiber Forms

Fiber reinforcement for polymer matrix composites comes in a variety of forms. Available forms depend on the reinforcement material and matrix, ie. aramid fiber is available in certain forms that glass and carbon are not and fibers intended to be used with a thermoplastic rather than thermoset plastic have different surface properties. In general glass and carbon fibers are available in similar forms, while aramid, due to its processing and handling properties is available in forms consisting of smaller diameter fibers as well as those common to glass and carbon. While virtually any combination of size, weave or material is possible, a semi-standardized variety of forms are available for cost effective production and for a convenient input for manufacturing processes.

The scope of this information pertains to fiber reinforced thermoset polymer matrix composites, more specifically the three most common reinforcement materials, glass, carbon and aramid. General forms include: milled fibers, chopped fibers, single strands, rovings or tows, random discontinuous fiber mats, unidirectional ribbons, woven fabrics and multi-layer woven fabrics. The information contained will pertain to advanced composite materials therefore discontinuous fibers will not be discussed.

Single strands are rarely used alone, they are more commonly grouped together in a larger bundle referred to as a tow, roving or yarn. These bundles range in size from 1000 to 200 000 fibers, with 3000, 6000, 12 000, 24 000 and 48 000 single strands being the more common forms [7]. Tows have a variety of uses; they are commonly used to produce chopped fibers in situ with aforementioned chopping/spraying guns or used in filament winding machines. Tows are characterized by their linear weight, either tex (weight in grams for 1000 meters) or denier (weight in lbs of 10000 yards).

The most common use for tows is in woven fabrics. Woven fabrics are produced by weaving tows using standard textile weaving methods. A variety of characteristics can be produced by a combination of tow size, material and weave pattern. Some important characteristics of woven fabrics are drapeability, or the ease at which the fabric conforms to 3D curves and shapes, permeability, or the ease at which fluid can travel through the fabric (an especially important property in RTM), saturation ability, or the ease at which fluid will fully saturate the fabric (another important property in RTM), strength, stiffness and the fabrics ability to be cut and shaped while maintaining its form.

Two-dimensional fabrics have two axes, the x-axis that runs the width of the fabric, generally 36 to 120 inches long and is referred to as the fill and the y-axis that runs the length of the fabric, generally 100 to 500 feet and is referred to as the warp. There are three weave styles that are commonly available: the plain weave, basket weave and satin weave. The plain weave is found everywhere from cotton T-shirts to sail boat sails and consists of the first fill running over then under the first two warp while the second fill runs under then over the first two warp, this basic pattern, known as the ‘pattern repeat’ is then repeated throughout the entire fabric. A basket weave is a variation of the plain weave where the first two fill run over then under the warp while the second two fill run under then over the warp. There are a variety of satin weaves; they are classified by a harness number. The fill in a satin weave will go over one warp then under a number of warp before it crosses over the warp again. The harness number refers to the number of warp plus one that is not woven. For example a five-harness satin weave will cross over one warp then under four before it crosses over a warp again.

The plain weave is the tightest of the three and therefore most resistant to in-plane shear movement, this also makes it the least drapeable of the three. The satin weave has the least resistance to shear movement, which makes it the most drapeable. Due to the looseness of the weave satin fabric is the most delicate and difficult to handle during processing.

The edges of fabrics are generally finished with a special weave running in the warp direction to keep the weave together. This is known as a locking leno and consists of one warp running over the fill then under while another warp runs under a fill then over the next.

Another type of fabric is a unidirectional fabric. This fabric consists of unidirectional tows in the warp direction woven together with a plain weave of tows with a much lower strand count. Fabrics are also classified by their areal weight in either ounce per square yard or kilogram per square meter.

2.5 Matrices

The matrix in a polymer matrix composite has three responsibilities: transfer of stress between the fibers, protect the surface of the fibers from mechanical abrasion and provide a barrier against an adverse environment. The matrix material plays a key role in certain loading cases and greatly affects the strength of a component. The matrix has a major influence in the interlaminar shear properties and in-plane shear properties. The interlaminar shear properties are important when a component is subjected to bending loads while the in-plane shear properties are important when a component is subjected to torsion. The matrix also provides lateral support, which contributes to a component’s buckling properties and therefore compressive strength. The matrix has little influence on the tensile properties of a component.

As mentioned above, composites are generally classified according to their matrix material. There are also sub-classifications within each type of composite material. A PMC could be, for example: polyester, epoxy, polyimide, etc. while an MMC could be aluminum, titanium, etc. There are generally two types of polymer matrices, thermoset and thermoplastic. Thermoset plastic is the most common matrix and makes up over 80% of the matrices in reinforced plastics [7]. The two most common types of thermoset plastic are polyester and epoxy. Only thermoset plastics will be discussed in this thesis since they are the most relevant to RTM.

2.5.1 Polyester

Polyester resin is the most commonly used matrix due largely to the combination of price, versatility and reasonable mechanical properties. There are a variety of polyester resins, all of which start with an unsaturated polyester resin. The properties of polyester resins may be tailored to produce a desirable combination of viscosity, cure time, strength, stiffness and strain to failure. As a rule the toughness of the material is traded off for thermal performance, in other words, the higher service temperature, the more brittle the material.

A major disadvantage of polyester over epoxy is its high volumetric shrinkage. This shrinkage causes uneven depressions on molded parts however it does make molded parts easier to demold. Polyester resins are also sensitive to ultraviolet radiation resulting in reduced mechanical properties and discoloration. An ultraviolet stabilizer may be applied to the outer surface of the material to virtually eliminate this problem. Polyester resins release more volatile chemicals when curing than epoxies and therefore, more safety precautions are required when working with them.

Polyesters are commonly used in less critical applications such as boats, cars, shower stalls, hot tubs, surfboards and pick-up truck canopies.

2.5.2 Epoxy

Epoxy resins are the matrix of choice when it comes to high performance applications and used in virtually all aerospace applications. Epoxy resins are a broad group of thermosetting polymers in which the primary cross-linking occurs through the reaction of an epoxide group. The molecular structure of these polymers varies drastically allowing for a very wide range of properties, even more so than with polyester.

There are three elements to an epoxy resin, the base resin, the curative or hardener and the modifiers. Each of these elements can be modified to tailor the properties of a specific epoxy. Most epoxy formulas are proprietary. The base resin defines certain properties of the final product such as operational temperature while the hardener defines the curing properties such as time and reaction initiation type (heat initiation or mixing initiation). Modifiers are added to produce specific physical and mechanical properties both before and after curing. Modifiers may also be added to provide properties that would otherwise not be present such as flame retardant or pigment.

Along with its tailorability, advantages of epoxy include low shrinkage during cure, an absence of volatile vapors during cure (common to polyester), excellent resistance to chemicals and solvents and excellent adhesion to reinforcement. Disadvantages of epoxy include its relatively high cost, difficulty to combine high temperature resistance and toughness, high thermal coefficient of expansion and the resin and hardener are somewhat toxic in their uncured form.

2.6 Prepreg Material

A pregreg (short for preimpregnated) is a type of composite constituent in which the resin and reinforcement are already combined. Prepreg material is available in woven mat and unidirectional fiber with a very tight tolerance on the fiber placement and volume fraction of resin/fiber. The workability of this material is excellent, as the operator only has to worry about the placement of the prepreg rather than mixing the resin and fiber. Prepreg is generally only available as carbon and epoxy. The hardener is already combined with the epoxy and heating initiates the cure. Since the hardener is already mixed with the resin prepreg has a shelf life. This is generally around one year or so. Some prepreg requires cooling during storage to prevent it from curing.

2.7 Manufacturing Processes

The key difference between manufacturing with traditional materials such as metals is that composite materials and components are produced at the same time as opposed to traditional materials where the material is produced in one process and the component is produced in a second process by forming, adding or removing material. The manufacturing process used to produce a composite material/component has a large bearing on the quality of the finished component and must be taken into account during the design stage.

There are numerous manufacturing processes commonly used to produce composite components. The basic process of producing a fiber reinforced, polymer matrix composite part involves saturating the fiber reinforcement with the matrix, shaping it to the desired shape and allowing it to cure. The technique employed depends on budget, production volume, geometry, performance, quality and expertise. Different techniques produce components with different levels of quality, variation of quality and performance. Some techniques require a large one time initial investment such as a mold or die making them conducive to larger scale production. The five most common fabrication methods are hand layup/spray up, prepreg/autoclave molding, filament winding, pultrusion, and RTM and its variants. These techniques are briefly described in the following sections.

2.7.1 Hand Lay-up and Spray-up

Hand lay-up is the oldest and most commonly used manufacturing method. This process requires little initial investment but is labor and skill intensive. Components that are laid up by hand are one off and not highly repeatable. The quality of these components is generally less than alternative techniques. To achieve a higher quality sometimes a vacuum bag is used. This involves placing the mold in a large bag and vacuuming the air out. The purpose of this is to reduce air bubbles in the matrix and remove excess resin. This technique is often referred to as vacuum bagging.

Spray-up is another common production method that involves spraying chopped fibers saturated with matrix on to a mold with a purpose built gun or nozzle. Often a gel coat is applied to the mold prior to produce a better surface quality and protect the composite from the elements. This process requires a mold and like hand lay up is labor and skill intensive. Since the fibers are short (on the order of ~1 inch), parts produced with this technique are not as high performance as those made from continuous fibers and are not classified as ‘advanced composites’.

These two techniques are generally used to produce polyester resin parts such as boat hulls, tanks and vessels, pick-up truck canopies, sinks, hot tubs and surfboards. The pros of these processes include: low initial start up cost, easy to change mold/design and on-site production is possible (ie portable process). While the cons include: highly labor intensive, the quality of parts dependent on operator’s skill and is somewhat inconsistent and the part has only one good side. Figure 2-1 shows examples of hand lay-up and spray-up. Notice the protective equipment both operators are wearing, both of these techniques require safety equipment due to the close contact with the materials.

Figure 2-1 Hand lay-up (left), Spray-up (right)

2.7.2 Prepreg Lay-up

In the prepreg process a piece of prepreg is cut to shape and laid up against a mold to achieve the desired shape. The mold and prepreg are then sealed with a plastic or rubber material to allow a pressure to be applied to the composite. The mold and prepreg are then placed in an oven to cure. While in the oven a pressure is applied via the cover. The pressure is applied with either a vacuum that is applied inside the cover thereby creating nearly one atmosphere of pressure or by an autoclave oven which pressurizes the entire oven with the potential to create up to 5 atm or more. Due to the higher pressure achievable with an autoclave, this method is used in higher performance applications. The higher pressure compacts the prepreg more that helps to remove excess resin, which in turn creates a product with a higher fiber volume fraction.

The use of the prepreg technique is very common in aerospace and high performance composite applications due to the high quality of parts produced, the control over the fiber placement and fiber volume fraction. The drawback of this technique is intensive manual labor, cost of prepreg, limited shelf life of the prepreg and only one quality surface is produced.

Another technique used with prepreg material is automated tape lay-up. This process uses a cnc machine to roll the prepreg on to the mold. This process is highly repeatable since it is a machine controlled operation and has the capability of producing large 3D parts.

2.7.3 Filament Winding

Filament winding is a common form of composite processing that produces very high quality parts however is limited by the possible shapes it can produce. With filament winding a continuous reinforcement, either previously impregnated or impregnated during winding is wound around a rotating mandrel to form a composite component. Once cured the mandrel is either left in the part or removed. Parts produced with this technique are limited to semi axi-symmertic parts due to the winding process.

The advantages of this process are it's high production speed, very accurate and repeatable parts and the use of continuous fiber. The shortcomings of the process include expensive winding equipment, high mandrel cost, poor surface finish and the limitation on the shape of the part. Commonly produced parts include lightweight oxygen bottles for firemen, hydrogen storage tanks, rocket motors and drive shafts. Figure 2-2 shows a schematic of this process.

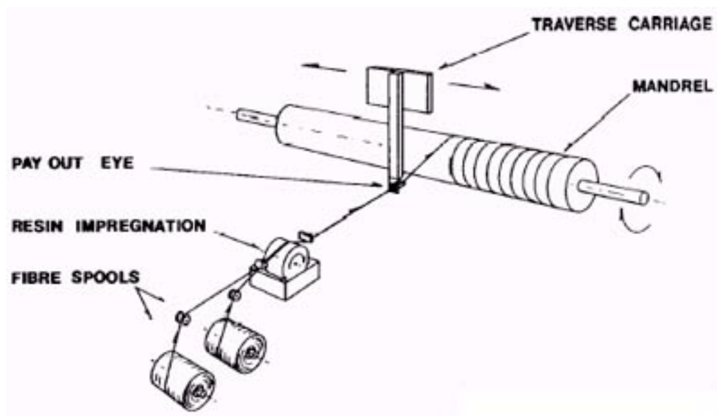

Figure 2-2: Schematic of filament winding

2.7.4 Pultrusion

Pultrusion is similar to extrusion of metal and plastic shapes. It involves pulling resin-impregnated continuous fiber strands through a die to produce an extruded shape. This process is highly repeatable and allows for a high level of control over processing parameters. The cost for the extrusion machine is expensive and a specific die is required for each shape. Standard extruded shapes can easily be produced such as pipes, C-channels and I-beams. One limitation of this process is the fiber orientation; fibers can only be placed axially along the length of the extrusion limiting the applications of parts created with this process. For example, pipes produced with this process would not be able to withstand high pressure since the tensile strength provided by the fibers does not act in the same direction as the hoop stress.

2.7.5 RTM and Variants

Resin transfer molding is the focus of this thesis and a thorough background understanding of the process is essential in understanding the purpose of the work presented here. RTM is not a new process. The first documented reference of its use was in 1946 [4], however it has not yet received widespread popularity. This is partly due to the trial and error nature of the process and the lack of understanding the common design engineer has of the process. RTM has the potential of becoming the dominant low-cost process for the fabrication of large, high-performance products for the consumer segment of the economy [1].

2.7.5.1 Process Description

Resin transfer molding (RTM) and variations of the process can be grouped into a family known as *liquid composite molding*. These processes share the basic underlying principle that liquid resin is injected through a stationary fiber preform. Injection is induced by a pressure gradient acting across the preform. The manner in which the pressure gradient is created, the nature of the tooling and the type of resin injected defines the process.

The basic operation of the processes involves loading a fiber preform in to a mold cavity, closing the mold, injecting resin into the mold and allowing the resin to cure. The variations on how this is actually performed determine the process. Aside from the basic method or resin transfer molding there are four common variations used to perform this process: structural reaction injection molding (SRIM), vacuum assisted resin injection (VARI), vacuum infusion and injection compression molding.

SRIM involves the use of a polyurethane resin that reacts quickly once initiated. The low viscosity resin and initiator are injected at a high flow rate via a metering injection system, which delivers the appropriate ratio of the two components. The mixed resin flows through the mold and cures in a matter of minutes, hence the high injection rate. The benefit of this process is the rapid cure rate of the component and therefore high production rate, however it is limited to polyurethane resins.

VARI differs from traditional RTM by the application of a partial vacuum to the mold. This vacuum helps to hold the mold together, reduce deflection of the mold due to reduced pressure inside the mold, increase the pressure gradient across the preform and remove air from the mold cavity. This process does not differ greatly from RTM, however generally produces better quality components due to the removal of air in the mold. Like RTM, VARI generally uses polyester and epoxy resins.

A natural progression of VARI is vacuum infusion. Like VARI, vacuum infusion uses a vacuum (greater vacuum than VARI) that is applied to the mold. However the purpose of this vacuum is more to create the driving pressure gradient rather than just assist it. With this process a one sided mold with a vacuum bag is used rather than a fully rigid mold. This reduces equipment costs and makes the transfer of resin more efficient as the resin can travel between the vacuum bag and fiber to later saturate the fiber as it travels transversely through the preform. The use of a vacuum bag however, produces a good finish on only one good side. This process is also referred to as vacuum assisted resin transfer molding (VARTM).

Another variation is injection compression molding. With injection compression molding, the mold is partially separated during injection in an attempt to increase the permeability of the preform. After the resin is injected (at a greater rate than could be achieved when the mold is completely closed) the mold is fully closed, compressing the preform and resin to the desired shape. The benefit of this technique is the increased injection time. A variation of this process is the Seeman Composite Resin Infusion Molding Process (SCRIM) where a one-sided mold and vacuum bag are used. The resin is injected into the mold/vacuum bag at a high rate and compressed with the vacuum bag. The benefit of this process is the capability of producing very large parts such as a ship hull due to the increased injection rate and use of a less expensive one sided mold although because of the use of a one sided mold, components made with this process only have one good side.

2.7.5.2 RTM Advantages and Disadvantages

As with every processing technique there are inherent advantages and disadvantages due to the nature of the process, naturally RTM is no different.

One major advantage of the RTM process is the fact that it can be applied to a wide range of manufacturing objectives. The tooling and equipment can be created economically to suit one-off production or higher volume production however the range of interest is up to 35 000 units per year [7].

RTM has the capability of producing complex shaped 3D components. Since a closed mold is used, components have a good finish on all sides with a class one automotive surface finish possible.

Inserts are easily positioned and embedded and a tight control over the fiber placement and fiber volume fraction is possible. A tight dimensional tolerance is possible and both shape and tolerance are highly repeatable.

Since RTM is a closed molding process all potentially harmful vapors can easily be captured and treated as necessary. Operators are minimally exposed to these vapors, which makes for a much safer work environment than almost every other processing method.

The RTM process can be numerically modeled and optimized, a capability that is not inherent to all processing methods.

RTM is not without its drawbacks. Molds are often designed using trial and error methods and are not guaranteed to work without modification although advances in modeling and a better understanding of the process is making this less of an issue.

A phenomenon known as “race tracking” may occur. This is when the resin goes around the reinforcement rather than through it. This is discussed in more detail in the following section.

A phenomenon known as “wash out” may occur during injection. Wash out refers to the resin displacing the fiber rather than flowing through it. This is often caused by an undersized preform or mold deflection and can be remedied by properly sizing the preform or reinforcing the mold respectively.

RTM is relatively sensitive to processing parameters and inlet/outlet port position. With unacceptable parameters and port placement voids are easily formed. Since most molds are not transparent it is hard to tell if a mold if fully saturated during injection, which can also lead to voids.

2.7.5.3 Racetracking

RTM has some inherent issues that still must be dealt with before widespread use of the process will take place. These issues are not detrimental to the technique however they are not trivial and must be accounted for during mold design and operation. Much research is being done to quantify, characterize and simulate these issues.

As mentioned earlier, racetracking is an important practical problem that has a very influential effect on nearly every aspect of the RTM process from designing the mold to preparing and loading the preform to injecting the resin. If not properly considered racetracking can render a mold useless by trapping air pockets in the molded part thus making the parts produced useless.

Racetracking occurs when the injected resin takes the path of least resistance creating an uneven flow front. It most commonly occurs when molding shell structures where the preform consists of fabric cut to size and laid in the mold with the edges of the fabric coming in contact with the edges of the mold rather than 3D structures where the edge of the preform is not butted up against the edge of the mold. This is why a flat panel shape has been selected to study this phenomenon. There are generally two common causes of racetracking. One reason this occurs is due to the mold flexing and displacing during injection under pressure allowing resin to flow between the preform and the surface of the mold. This situation can be remedied by reinforcing the mold to make it more rigid and can be avoided by designing the mold to be as rigid as is required prior to manufacturing the mold. The second cause of racetracking is much less trivial and in certain situations cannot be avoided. This type of racetracking occurs on the outer edges of a mold where sheets of woven fabric preforms meet the edges of the mold. There are two reasons this occurs; undersized preforms that do not butt up against the edge of the mold closely and fiber that is lost from the edges of the fabric during handling creating a lower fiber volume fraction and greater porosity and permeability at these edges. This puts more emphasis on the importance of producing an accurate and repeatable preform.

While not always completely avoidable, racetracking can be reduced and controlled in a number of ways. When a mold is designed the injection port and outlet port location are very important. Their location can effect the time to fill the mold, weather or not the mold will fill entirely and the sensitivity of racetracking. In the experimental 2D mold, the injection port is located at one end of the cavity while the outlet ports are located at the opposite end. This causes the fluid to flow from one end of the mold to the other thereby giving racetracking an opportunity. However, if the injection port were located directly in the middle of the mold, causing the resin to flow out radially, then there would not be an opportunity for racetracking. Manually producing and loading the preform opens many opportunities for inaccuracy and damage to the preform, which in turn cause racetracking. This can be reduced if the entire process is done by machine. Some molds have the ability to produce the preform by shearing the edges of the fabric to size with the edges of the mold. These molds are quite expensive and must be made out of special materials to stand up to the abrasive reinforcement material.

While the author has not come across any documented reference of anyone using racetracking in their mold designs there is an opportunity to use racetracking as an advantage to help fill the mold faster. For example, racetracking could be designed to occur along certain edges to bring resin to regions farther away from the injection port in an attempt to fill those regions at the same time as regions closer to the injection port.

2.7.5.4 Micro and Macroscopic Flow

During injection there are two scales of flow that occur as the resin attempts to saturate the fiber. This is due to fiber orientation and geometry. Woven fabric is made of bundles of individual fibers called tows that are woven together as can be seen in Figure 2-3 a and b. The flow of resin around the tows is referred to as macroscopic flow and can be easily seen with the human eye while flow through the individual fibers is referred to as microscopic flow and cannot be seen with the human eye. Macroscopic flow is governed by the pressure gradient across the mold while microscopic flow is governed by capillary pressure between the individual fibers, which is a function of surface tension. If these two flow fronts do not proceed simultaneously then the mold will fill before the fiber is fully saturated creating microscopic dry spots. Figure 2-3 c helps to describe this phenomenon.

Figure 2-3: a) close up of a tow, b) close up of woven cloth, and c) schematic of macro and microscopic flow

The progression of these two flow fronts can be controlled by the injection pressure, the permeability of the reinforcement and resin surface tension. The more permeable the reinforcement the higher the injection pressure gradient may be and therefore faster the fill time. Special chemicals can be applied to the reinforcement to lower the surface tension and assist saturation. Chemicals can also be added to the resin for this purpose.

2.7.5.5 Process Variables

There are three main process variables that can be adjusted to control the performance of an RTM system. These are the ease at which the resin saturates the fiber, the injection pressure or velocity and the resin and mold temperature.

The ease at which the resin saturated the fiber is a function of the fiber volume fraction, permeability of the fiber and surface tension of the resin and fiber. The fiber volume fraction can be controlled by the size of the preform, however the preform must maintain an acceptable size so that it is not displaced during injection. The permeability of the fiber is a function of the fiber diameter, tow size and type of weave. There are a number of sizes and styles of fiber that may be used as preform.

The pressure gradient across the preform or the “injection pressure” and the injection velocity have a strong effect on the mold fill time and the quality of the component. There are two injection options, a constant injection pressure as with a pressure pot or a constant injection velocity as with a resin injection pump. The difference in performance lies in the fact that the constant velocity method will fill the mold at a constant velocity/volume flow rate while the constant pressure method will gradually slow the inlet velocity/volume flow rate as mold becomes more full. It is commonly accepted that the flow of resin through the mold is governed by Darcy’s law of flow through a porous medium, which states that the pressure and velocity are linearly related. If the pressure/velocity is too high, then the microscopic flow will lag the macroscopic flow and cause the formation of voids. Reducing the pressure/velocity makes the filling process take more time. Optimizing the injection pressure or injection velocity lies in finding the maximum pressure or velocity such that the micro and macroscopic flows progress at the same rate. A higher pressure may also cause the fibers to displace, disturbing a precise fiber pattern or may cause the mold to bulge which may lead to more racetracking or possibly damage to the mold.

The temperature of the resin and mold during injection play a role in the viscosity of the resin and, taking into account Darcy’s law the pressure and velocity of the resin are related to the viscosity of the resin. The higher the temperature the less viscous the resin becomes. Raising the temperature of the resin causes it to cure more rapidly, which may be a problem if it starts to gel while the mold is only half full. Resins that are designed to be injected generally have operating guidelines that dictate the injecting temperature of the resin.

2.7.5.6 RTM Specific Constituent Materials

As with any specialized composite material processing technique, RTM has specific resin property requirements and resins developed specially for this process have been formulated and are available commercially. There are two important requirements for a resin to be suitable for use in an RTM process; the resin must have a relatively low viscosity and long working time. The viscosity of the resin is important in RTM because the resin must flow through the fiber, this is specific to RTM because the resin does not flow through the fiber in any other processes. An RTM resin will have a viscosity somewhere around 150 cps to 1000 cps. According to Darcy's law, the higher the resin the lower the velocity or a greater pressure gradient is required to achieve a desired velocity compared to a resin with a lower viscosity. If the viscosity is too high then there is more viscous force on the fiber and a higher chance of fiber displacement. A long working time is required for an RTM resin so that there is enough time for the mold to fill before the resin starts to gel. The working time for an RTM resin is around 100-300 minutes. This usually gives the operator time to mix the resin, degass it, inject it and clean the equipment before the resin starts to gel. As one can imagine there would be big problems if the resin cured while still in the injection equipment or midway through the injection process. The injection temperature is not a major concern with RTM resin however it does come into play regarding the resin viscosity and gel time. The viscosity of the resin decreases as the temperature increases as does the gel time. Compatibility with other materials such as foam is another concern with RTM resin. Foam cores are commonly used with RTM however some resins dissolve foam. The additives used to lower the viscosity of resin such as styrene are also corrosive to certain foams and other materials. It is best to check the specifications or formulation of a resin to see if it is compatible. As with most processing methods, the ability to wet out the fiber is important with RTM resin to reduce trapped voids. As mentioned earlier, chemicals are added to the resin to increase its wet out ability.

For the most part fiborous reinforcement forms used in RTM are the same as or very similar to those used in hand lay-up and press molding although there are some RTM specific materials on the market.

The most important reinforcement characteristic for RTM is the permeability, or the ability for fluid to flow through the reinforcement. This depends on a number of variables such as fiber architecture, fiber compression and fiber volume fraction. Generally speaking the permeability increases exponentially with increasing fiber volume fraction

[7]. The fiber architecture plays an important role in the permeability. Random mats usually have the highest permeability due to the random placement of the fibers and a lower fiber volume fraction than woven material. Quasi-unidirectional mat can have a high permeability in the fiber direction and a lower permeability perpendicular to the fiber direction while woven mat generally has the lowest permeability. Darcy's law states that the pressure is proportional to the permeability; this shows that the permeability of a reinforcement material has an impact on the processing equipment due to its relationship with injection pressure and internal mold pressure. The permeability of a reinforcement is a property that must be obtained empirically as it varies depending on the mold, compaction and other parameters.

The formability or drapeability of the reinforcement is also of concern when 3D shapes are formed. The fiber architecture dictates the drapeability of the reinforcement.

One area in which fiber reinforcements for RTM applications vary differently from other processing methods is in preform construction. Generally speaking most other processing methods simply require a piece of fabric to be cut to size however RTM has the ability to incorporate complex 3D preforms. These preforms are usually knitted to a desired shape or thermoformed into shape with the aid of a thermoplastic binder material to maintain this shape. Knitted preforms offer the greatest potential for high quality 3D composite components since there are no seams in the preform. Once example is a knitted 'sock' that is fitted around a foam core to produce propeller blades.

Naturally there are reinforcement forms that are made specifically for RTM, these are aimed at controlling the permeability. One such example is a product called Rovicore made by Cormarat of France. This product is composed of a highly permeable, conformable polypropylene mesh sandwiched between two layers of glass fiber random mat. This product is useful because it conforms to the shape of a mold well and the mesh increases the permeability of the reinforcement dramatically over woven reinforcement although the fiber volume fraction of this material is quite low. Some woven fabrics are available that have a weave pattern that incorporates channels of higher permeability in an attempt to help the resin flow through the material better. The draw back of both of these materials is the compromised fiber architecture, which results in lower mechanical properties of the component.

Chapter 3 DESIGN AND OPERATION OF ADVANCED COMPOSITES LABORATORY

3.1 Introduction

This chapter discusses the design and construction of the resin transfer molding apparatus and the laboratory facility that houses it. To reiterate, the motivation of this project is to design, build and test a laboratory scale resin transfer molding system that can also be used study the flow of resin through the fiber during injection and characterize this flow using computational fluid dynamics techniques.

The design began by laying out some objectives and constraints. What was to be done, how it would be done and why it would be done was the first step in the design. Once this was determined, brainstorming possible solutions began. A number of the most promising solutions were selected and modeled using a solid modeling software program (SolidWorks 2007). These solid models facilitated more brainstorming and brought more practical design considerations to light. From these models design changes and refinements were made and the best candidate design was selected. This facilitated further and more detailed design, which led to the final design. The design of the apparatus also included the design of the laboratory facility. What materials and equipment was required to have on hand, the layout of the area and safety issues were all part of this design. While considered during the design, manufacturing techniques and logistics became the next major challenge. How to manufacture, where to manufacture, how to explain the design to those manufacturing it and how to stay cost effective became the next challenges. Once the parts were produced the apparatus was assembled and any required modifications were made. After this stage the apparatus was ready to be tested and used for experimentation.

3.2 Objectives and Constraints

Before any work on the design could begin the objectives of this work had to be laid out. Constraints on the operation and performance of the apparatus also had to be defined prior to the design stage. These would serve as the foundation of the final design.

The objective of this project is to produce an RTM apparatus to study the flow of resin through fiber reinforcement during injection. Visual inspection of the flow is the best method to monitor the flow pattern and therefore the constraint to install a transparent viewing window in the mold was the first objective.

A maximum working pressure of 90 psi was selected based on operating specifications of injection pumps available on the market.

Aside from the exclusive use of thermoset plastic resins, there is no constraint on the type of resin to be used in the mold. This means the mold must be designed to use a variety of resins. The majority of resins used in RTM require operating and curing temperatures above room temperature and generally below 100 °C. The chemical reaction that occurs during the curing of the resin is an exothermic reaction, which means the resin produces heat during curing. If too much heat is produced the resin will cure too fast resulting in undesired physical properties such as brittleness. To avoid this a temperature controller that can both heat and cool the mold must be used. This temperature controller must be separate from the mold cavity to reduce manufacturing complexity and the number of parts of the mold its self. If the mold cavity is replaced the temperature controller does not.

The material that the mold is made from has an influence on the performance, durability, cost and manufacturing method. Commonly used materials include casting resins, aluminum, nickel-plated steel and tool steel. Due to the performance, durability, machine-ability, thermal conductivity, availability and cost, aluminum was selected as the material to make the mold from.

One person must be able to operate the mold with reasonable ease. This means no heavy lifting, the mold is manipulated easily and all associated equipment is easily accessible and mobile. Depending on the design this may mean that a built-in lifting device to separate the mold halves is required. This also means that the mold itself must be mounted on a base with wheels so that it may be repositioned if necessary.

Molds are held together using a number of methods. Hydraulic presses, bolts and clamps are the most commonly used and their selection depends on the operation type (high volume production or one off experimentation), load/pressure on mold and budget. Hand clamps were specified for this mold because of the ease of use, carrying capacity and cost. An alternate choice would have been bolting the two halves together. This option has the potential to carry a greater load however much more time is required to assemble and disassemble the mold.

Two mold shapes will be used in this apparatus, a quasi 2-D shape (thin rectangular panel) and a 3-D shape (hollow rectangular and semi-circle bar), therefore the whole apparatus must be modular to accommodate a variety of mold shapes. This means that various thicknesses of mold plates may be used with minimal modification to the existing apparatus.

3.3 Layout of the System

The general layout of the experimental apparatus is shown in Figure 3-1 and Figure 3-2. The equipment is modular in the sense that it can incorporate a variety of molds and mold sizes as well as injection and temperature control systems. The apparatus can be separated into seven separate components: the injection system, mold, manipulating/clamping apparatus, catch pot and vacuum system temperature control system and data acquisition system.

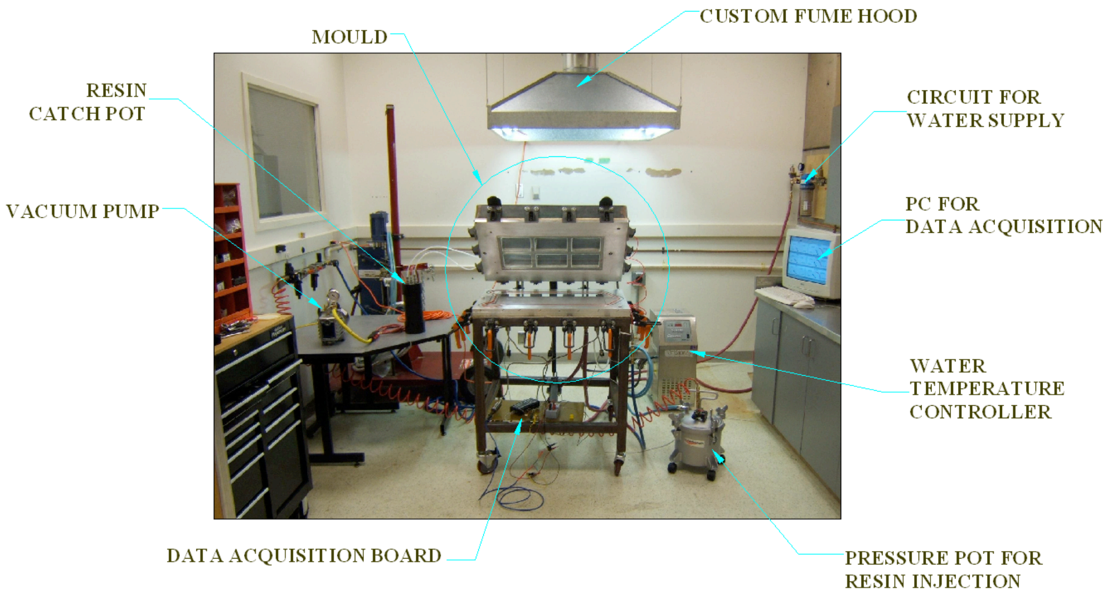

Figure 3-1: Layout of the lab

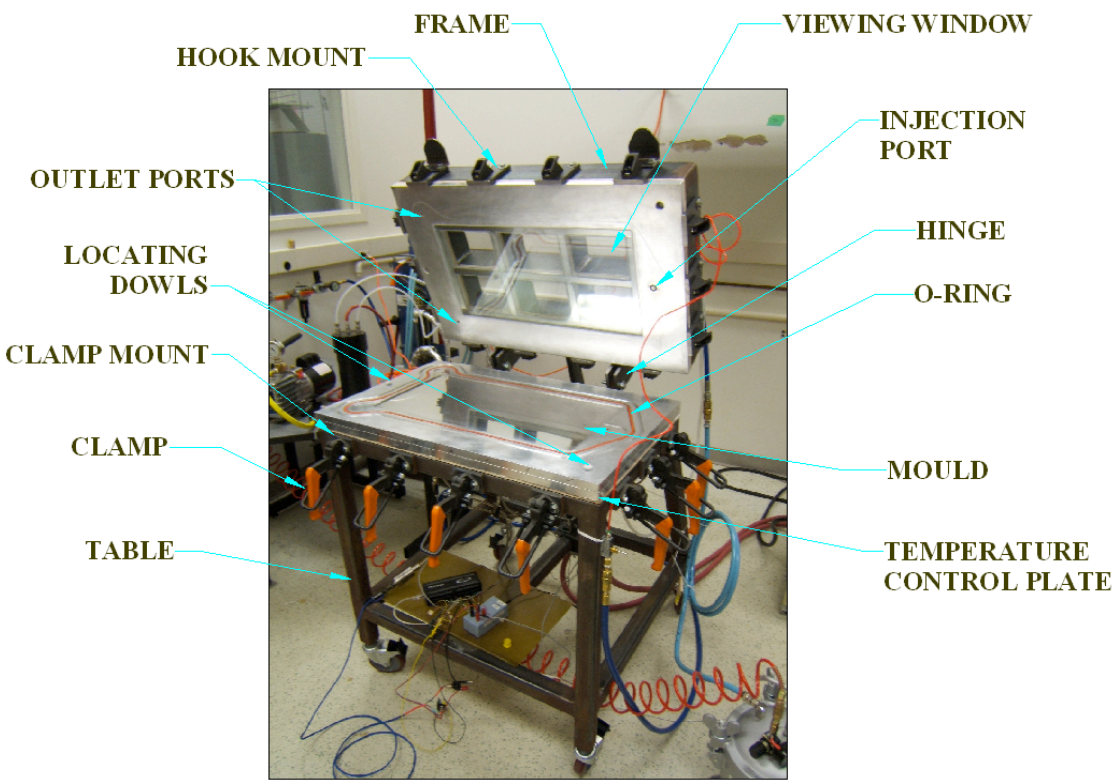

Figure 3-2: Layout of the RTM apparatus

Considering the objectives and constraints, a clamshell style manipulating device with independent injection, temperature control and outlet control systems was selected. Since these systems are separate they may be interchanged for alternative systems at any time. This also allows for easy manipulation of the mold and provides a good base to mount associated components to. Alternative styles could have been a hydraulic press type system, where the mold is mounted on and manipulated by a hydraulic press or an independent system consisting of just the mold and clamped together with bolts. The hydraulic press system would have been far more costly although it would make the mold more accessible. The capacity of a press type of system would have far exceeded the needs of this RTM making it over designed and over priced for this purpose.

3.4 Background, Design and Selection of Components

3.4.1 Injection System

The injection system consists of an injection device and injection valve. The injection device is responsible for injecting the resin while the injection valve is responsible for bleeding air from the injection system, sealing off the mold before and after injection and allowing the entire injection system to be flushed with a cleaning agent after injection. The injection valve must also be easily removed from the molded part during part removal.

There are two options commonly used for the injection device, a pressure pot or a resin pump. The selection of the appropriate device depends on production volume. A pressure pot is usually used for prototype and low production volume work while a resin pump is used for high volume production. The main function of the resin pump is to mix the two parts (the resin and hardener) to create the thermoset plastic matrix with an appropriate ratio and inject them into the mold. Pressure pots inject with constant pressure and varying flow rate while resin pumps inject with constant flow rate but varying pressure Resin pumps have certain advantages over pressure pot. The pump ensures that only the amount of resin that is needed is mixed which reduces material waste. Another advantage of the pump design is that the there is little clean up as the acetone flush is built into the machine.

As the name implies a pressure pot is a vessel that applies pressure to the resin to inject it into the mold. A pressure pot requires that the two-part thermoset plastic be mixed and loaded into the pot prior to injection. Mixing the two parts is a separate task that is usually done manually with a scale. Since the resin is premixed the entire amount will harden and cannot be reused.. Due to its operational simplicity and the small production volume, the pressure-pot based injection system has been selected.

The injection valve is an important part of the injection system. The valve is responsible for allowing resin to flow into the mold and sealing off the mold once the resin is injected. While this is the basic job of the injection nozzle there are more features that make an injection nozzle designed specifically for RTM beneficial. In the beginning of an injection the injection line is filled with air. This air would be forced into the mold as the resin is being injected and has the potential of creating air bubbles inside the mold. In the beginning of the injection the resin is often filled with air bubbles as well. To avoid the entrapment of air and purge the initial amount of air filled resin, a bleeding circuit is incorporated into the injection nozzle. This allows the initial amount of air and bubble rich resin to be pumped into a catch pot rather than into the mold. Since thermoset plastic hardens over time any equipment in contact with it must be cleaned prior to hardening. A well-designed injection nozzle will have a built in cleaning system, which simply allows acetone to be pumped through the previously mentioned bleeding circuit. Another feature of a well-designed nozzle is simple removal from the molded part. A flat surface in contact with the part while it is hardening usually allows for easy removal. One example of this type of injection valve is the Turbo Autosprue from Plastech as shown in Figure 3-3.

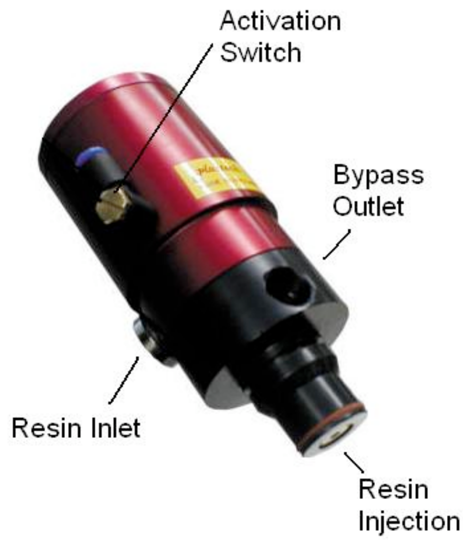

Figure 3-3: Turbo Autosprue by Plastech

3.4.2 Mold

While it appears that the mold is the heart of the system it is often an interchangeable part that has little to do with the design of the rest of the system. Virtually every commercial molding machine has a removable mold that can be changed to produce a different part. The mold is often housed in some type of clamping and manipulating apparatus such as a hydraulic press or clamshell system. The material, size, manufacturing method and features of a mold may vary considerably depending on the material being molded, the number of parts to be produced and available manufacturing resources and expertise. The clamping system is generally the major component of a molding machine and can vary greatly depending on production volume, mold pressure and mold size. In some cases a generic press may be used however clamping systems are often custom built.

The mold cavity dictates the final shape of the component as well as important characteristics such as the resin flow pattern, the presence of micro voids, the fill time and the repeatability of the parts produced. This apparatus is designed to allow the mold cavities to be interchanged. Two mold shapes are used with this apparatus, one quasi-2D shape and a 3-D shape. The quasi 2-D mold will produce a panel that is 1ft. x 2 ft., with a thickness of 0.13” and a 3-D mold will produce both a 1.5” square foam cored channel that is 20.5” long and a 0.75” radius semicircle foam cored channel of the same length.

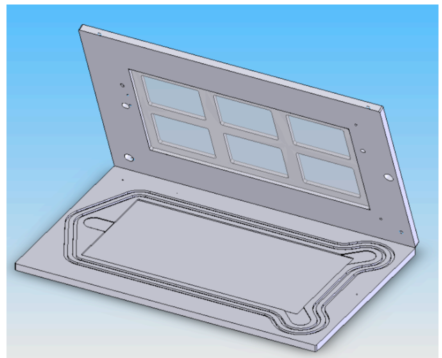

Figure 3-4: Solid model of flat plate mold

Figure 3-4 shows a solid model of the mold for the rectangular plate. The mold cavity consists of two ¾” thick 6061-T6 aluminum plates. The upper plate has 6 rectangular view ports. A piece of glass and polycarbonate are inset into the upper plate where the view ports are. As well as exposing the mold the glass provides a smooth molding surface for the upper surface of the component. The polycarbonate is a safety feature intended to contain the glass if it were to break. The upper plate houses the injection nozzle. A stainless steel insert is screwed into the plate to accept the nozzle. Any damage caused by removing and replacing the nozzle will be inflicted on the insert, which can easily be replaced. The upper plate also houses the two exit ports, which allow air to escape from the mold as well as a small amount of resin once the mold is filled. A Swagelock fitting is screwed into each port. These fittings allow a tube to be inserted through the mold while maintaining an airtight seal. Since the tubes will become filled with resin they may simply be thrown away and replaced with new tubing for each run of the machine. Four tapped holes on the outer corners allow the plate to be screwed onto the top frame. The lower plate has the mold cavity machined into it. Essentially the cavity is a 1’ x 2’ x 0.13” rectangle. The sides of the cavity have a 5° angle so that the component may be removed easily after molding. Three ‘rabbit ears’ are placed around the perimeter of the mold and are machined 1/16” deep. The two rabbit ears in either corner allow the resin to flow out of the exit ports while the single rabbit ear allows resin to enter the cavity. The locations of the ports were based on a pre-existing mold used by [5] that produced similar specimens. The lower plate also holds two o-ring glands, which accept two 1/4” thick silicone o-rings used to seal the mold. Four tapped holes on the outer corners allow the plate to be screwed onto the table.

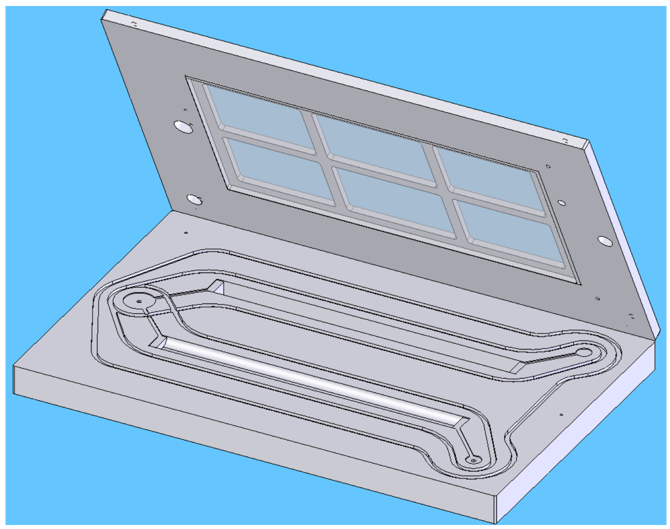

Figure 3-5: Solid model of 3D mold

The 3D mold shown in Figure 3-5 has the ability to produce two different parts: a rectangular section and a semi-circle section. The shape is selected by placing an o-ring around the desired mold shape. Only one part can be produced at a time with this mold. The inlet and outlet ports are in the same location as the other mold and the same top plate is used with this mold. One o-ring seals the mold shape and another o-ring seals the entire panel should the inner o-ring fail. The mold is machined out of a 2” thick plate of 6061-T6 aluminum and is fastened to the temperature control plate in the same manner as the other mold plate.

3.4.3 Mold Manipulating Apparatus

The mold manipulating apparatus is responsible for mounting, reinforcing, positioning and clamping the mold. The apparatus consists of four main parts, the table, top frame, clamps and spring system. The table supports the system and acts a base for most components to be mounted to, the top frame offers support to the mold to make it more rigid and acts as a base for the top of the mold to be mounted to, the clamps secure the mold closed during injection and the spring system assists in opening and closing the mold.

3.4.3.1 Table

The table supports the system and positions it at a convenient, workable height. It also helps to support the mold and make it more rigid so that it doesn't deform under pressure. It also acts like half of a press since the clamps are attached to the table. There is a piece of ¼" plywood sandwiched between the table frame and the aluminum plate that holds the heater core. The plywood helps to absorb any unevenness from the tabletop and acts as an insulator to prevent the heat from escaping from the bottom of the mold.

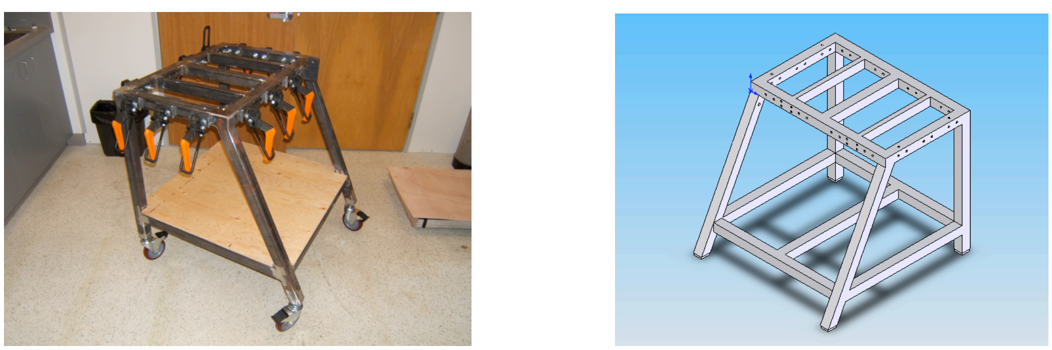

Figure 3-6: Photograph and solid model of the table

Figure 3-6 shows both the solid model of the table and the final product. The table is constructed, for the most part out of 2" x 2" x 3/16" hollow steel tubing. There are two cross members in the top frame of the table that are 1" x 2" x 3/16". These members are this size to allow hinges to be mounted on the back member of the table and still allow members to be located in that position. On the bottom of each of the legs is a piece of 2" x 2" x 1/2" steel plate with a ½-20 UNC thread in the centre. These plates allow the caster wheels to be screwed directly into the table without the need for bulky flanges, which could pose a safety hazard, as they would be sticking out from the table at ankle height. Since the casters are threaded into these plates, their height is adjustable so that the table can be leveled on any surface. The back legs extend back at an angle for two reasons. The main reason they're angled in such a way is so that the table will not tip over when the mold is opened to its fully open position. The reason that the legs extend that far back is so that when the legs are pushed against the wall there is still clearance for the mold to open without colliding with the wall or another obstacle.

The table is fully welded with no screwed or press-fit joints. The most important consideration when fabricating the table was how flat the table top would be as it would be holding and supporting the mold. The top four members that comprise the top of the table were all cut on 45° angles to produce a cleaner looking joint. When fabricating the table, two members were tacked to form two 'L' shapes. Once they were made square they were braced by welding a support across the tops of the two members (to form a triangle). After the members were braced they were fully welded knowing that the joint would stay square due to the bracing. After the two 'L' pieces were fabricated they were fit together and tacked. Once they were made square they were clamped down to the table and welded. The reason the top was fabricated in this manner, by joining two 'L' shapes together was to try to keep the top as flat as possible. Starting with two planes (the two ends of the 'L' and the joint are points, three points create a plane) and joining the last two corners greatly reduces the chance of the table becoming warped or uneven. The only variable to work with to keep the frame flat is the angle between the two 'L's since we know we are starting with two perfectly flat and square pieces. If the four members were fitted together and then welded there would be eight variables to adjust, the angle in each corner as well as how flat each corner is. Once the top of the table was fabricated it was just a matter of welding on the legs and cross members. As shown in the pictures there are quite a few holes in the top of the table, these are to bolt the clamps, hinges and the spring arm to. They were all drilled prior to welding when it was still possible to put the material in the milling machine. There was some concern whether the welding would cause the holes to move although the precision of the holes does not have to be that accurate, if the holes do not line up perfectly they can be reamed out slightly so that they fit.

3.4.3.2 The Top Frame

The top frame offers structural support to the top of the mold cavity and provides a place to mount the clamps, hinges and spring arm. It also provides reinforcement if the mold were to burst.

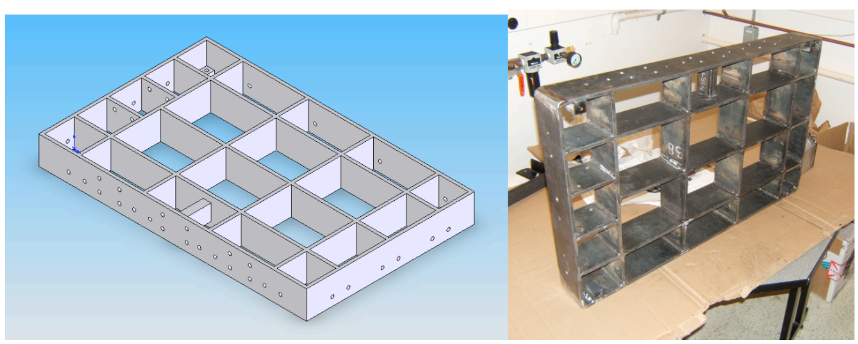

Figure 3-7: Solid model and photo of top frame

Figure 3-7 shows both the solid model of the frame and the final product. The frame was designed with this 'grate' shape to allow viewing ports to be placed in the mold as mentioned previously. The frame was also designed to allow the injection nozzle to be inserted into the mold. Aside from the small piece of 1" x 2" hollow tube used to support the spring arm the frame is constructed entirely out of 4" x 3/8" hot rolled, mild steel plate. The choice of 3/8" thickness was a compromise between strength and weight while the 4" width was used to provide an ample amount of inertia to provide rigidity. The width had a greater effect on the rigidity of the frame than the thickness of the material.

Like the table, the top frame is fully welded with no screwed or press-fit joints. A lot of time went into welding the frame. The most time was spent keeping the members square and properly aligned. The important consideration when fabricating the top frame was to keep the bottom as flat as possible. Since the frame will be pushing directly against the top of the mold, the bottom surface of the frame will be ground down so that it will not produce any pressure points that may break the glass. The flatter the frame is initially, the less material will need to be ground off. This will keep more of the initial 4” width making the frame more rigid as well as easier and less expensive to machine flat.

3.4.3.3 Clamps

The clamps used to secure the mold are shown in Figure 3-8. They are model: LU2000H toggle clamps supplied by HMC Brauer and have a maximum load rating of 4405 lbs. These clamps were ideal candidates for the design due to the large distance between the clamp and the hook. Most models require that the hook be mounted within about a ¼” of the clamp which would not leave room for the mold plates.

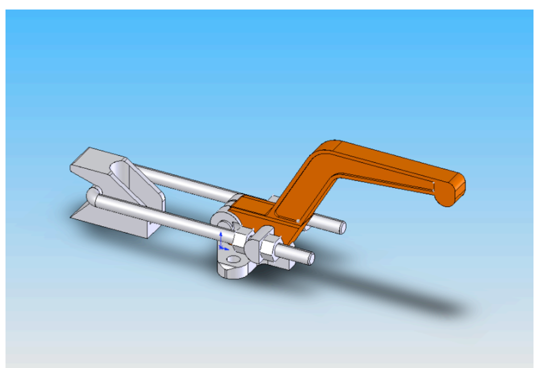

Figure 3-8: Solid model of clamp system

The main concern with the clamps was the method of mounting them. The material used to make the table was fairly thin; it would not allow us to tap and screw directly into it. There was also a concern of collapsing the tubing with the force applied by the bolts. These concerns were overcome by using mounting brackets on either side of the table frame and bolting directly through the frame. These brackets would distribute the load and reduce the chance of collapsing the tube. Only a bracket on the inside would have been required however, the clamps had to be spaced away from the table to meet with the hooks that are mounted on the frame. The hooks were positioned on the top frame so that they would have a cross member directly behind them; this would reduce the tendency to twist the frame out, causing the middle to bow upward. Unfortunately, this member interfered with the screw holes in the hook and required a mounting bracket. The bracket used simply allows the screws mounting the hook to be screwed directly into the bracket while two separate bolts are used to mount the brackets on the frame. This turned out to have the added advantage of allowing the hooks to be relocated by simply replacing the mounting brackets.

3.4.3.4 Spring System

The spring system assists in opening the mold and keeping it open. Its operation is similar to that found in the trunk of a minivan or hatchback car although due to physical constraints it must be placed in the middle rather than the sides.

Figure 3-9: Spring and Spring Arm

The system basically consists of three parts. The ‘L’ shaped spring arm, the reverse acting gas spring and the mounting bracket. Figure 3-9 shows the spring and spring arm. It is made out of a piece of 2” x 2” x 1/4” steel angle which is welded onto a base that is bolted onto the top frame. Another piece of angle is bolted onto the end of the first angle and extends down at a 90° angle. One end of the reverse acting spring (called a reverse acting spring because it pulls in rather than pushes out) connects to the back of the second piece of angle. The other end of the spring is connected to a cross member in the base of the table. The geometry of the system was designed such that when the mold is closed the spring is nearly fully extended and when the mold is open the spring is nearly fully retracted (it is recommended to design the system such that the spring is never extended to its limits). It is also designed so that the torque exerted by the spring nearly balances out with the torque exerted by the top frame producing a weightless effect.

3.4.4 Catch pot and vacuum system

The purpose of the vacuum system is to remove the air in the mold so that it does not create voids in the part, to bring the pressure down so that water trapped in the mold will evaporate and be removed from the mold and to create a larger pressure gradient across the mold to assist injection.

Figure 3-10: Vacuum pump (left) and catchpot (right)

There are two main parts that make up the vacuum system: the catchpot and the vacuum pump, both shown in Figure 3-10. The catchpot is located between the mold and vacuum pump. It is connected to the two outlet ports in the mold by two ¼" dia. polyethelyne tubes which run from the outlet ports of the mold straight into the bottom of the pot. Another tube runs from the top of the pot into the inlet of the vacuum pump. The principle of operation is that any liquid material vacuumed out of the mold is trapped in the bottom of the pot while the vapor is vacuumed out and expelled through the pump. The catchpot is made out of a 12" long piece of 4" dia. ABS plumbing pipe with an end cap on either end. The end caps are held onto the pipe with friction and sealed with o-rings. The top end cap has three fittings mounted onto it. Two fittings accept the tubing from the exit ports of the mold and allow the tubes to penetrate into the pot to reach the bottom. The other fitting simply attaches to a hose that connects to the inlet of the vacuum pump. One convenient feature of the catchpot is that the tubes are easily replaced so that when resin cures in the tubing then they can simply be thrown away. Catch pots are available commercially however due to there simple design and operation it is not uncommon to custom build them.

The vacuum pump used in this system is supplied by Torr Technologies, Inc. and is a roughing pump, model number 502150 rotary vane pump, shown in Figure 3-10. The pump's capacity is 5cfm of free air displacement, with a maximum vacuum of 29.91" Hg. It is driven by an integral ½ HP motor at 1725 RPM which runs off 115V at 60 Hz.

3.4.5 Temperature control system

The temperature of the mold must be controlled to ensure proper curing of the resin. There are a number of methods used to do this. The entire mold may be placed in an oven or autoclave to control the heat or the mold may have an internal heating system. There are two types of internal heating systems used, electric resistance heating or fluid heating (water or oil is generally the working fluid in this case). Each of these systems has their own advantages and disadvantages. Using an oven to cure the resin is more modular in the sense that the oven may be used for more than just this purpose and may be used for a number of molds with little to no modification. An internal electric resistance heating system is the least costly option, is simple and requires little equipment. However these two options do not allow for cooling, if for example the mold becomes too hot due to the exothermic reaction of the resin curing. An internal fluid temperature controller can both heat and cool a mold and keep it at a desired temperature regardless of the reaction inside the mold. This system is modular in the sense that a piping circuit is installed into the mold apparatus and the temperature controller is connected to this circuit. This allows for the temperature controller to be connected to a number of molds by simply disconnecting from one mold and connecting to another. Another method of temperature control involves the use of both a fluid temperature controller and electric resistance heating. These two systems may be used together to heat the mold faster and/or to higher temperatures.

Due to price and the capability of both heating and cooling the mold a fluid temperature controller was selected for this purpose. The controller is made by Advantage Engineering and is model SK-1035VE with a heating capacity of 10kW. The temperature controller uses tap water as the working fluid. The unit circulates water through a heater core that runs through an aluminum plate in the base of the mold referred to as the temperature control plate. The plate is sandwiched between the tabletop and the bottom of the mold and has a serpentine channel running through it. Two passes of ¼” copper tubing run through the channel. The water flows through the two tubes in different directions to produce an even temperature distribution. The temperature controller runs on a semi-closed loop. It pumps water through the heating circuit, the temperature of the water returning to the unit is measured and if the water is too cold the unit turns on the heater (or keeps it on), if the returning water is at the desired temperature then the unit turns the heater off, if the returning water is hotter than desired then the unit opens a valve and expels water out of the loop, while at the same time injects cold tap water into the loop. The temperature controller and heater core are shown in Figure 3-11.

Figure 3-11: Temperature controller (left) and solid model of heater core (right)

To achieve and maintain an elevated temperature in the mold, the apparatus is insulated. The insulation is in three forms and locations. A layer of insulation fabric is located between the table and the temperature control plate. A layer of polycarbonate is located between the top plate; polycarbonate was used because of its dimensional stability to reduce deflection in the mold. The pigeonholes in the top frame are stuffed with blue polystyrene insulation foam; the six holes covering the glass are removed during molding and replaced during curing.

3.4.6 Data acquisition

A data acquisition system (Omega OMB-DAQ-56, shown in Figure 3-12) is used to measure the temperature of the mold and the pressure of the resin inside the mold. Two types of sensors are used in the molds, one type is an Omega pressure transducer model: PX61V1-200GV and the other type is a combined 'J' type thermocouple and pressure transducer made by GP:50 model: 135-RH-GT. The panel mold has three GP:50 sensors installed flush along the bottom of the mold and two Omega sensors, one at the inlet and one at the outlet. The 3D mold has two GP:50 sensors, one at the inlet and one at the outlet of the semicircular mold. Proprietary Omega data acquisition software is used to monitor the DAQ and is run on a standard PC.

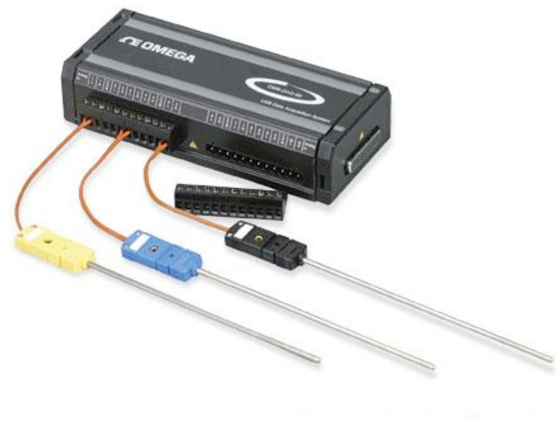

Figure 3-12: Omega data acquisition unit

3.4.7 Laboratory Setup

RTM apparatus must be operated in a suitable laboratory. This laboratory requires an area to operate, tools and equipment, ventilation, safety equipment and storage. The design of the lab was done in conjunction with the design of the RTM apparatus and built at the same time.

3.4.7.1 Layout of lab

The laboratory space used for this RTM system was designed from scratch to accommodate the apparatus and associated equipment and supplies and allow operation of this equipment.

The lab is separated into two rooms by means of a double standard sized door. The outer room is used for storage and miscellaneous tasks, while the inner room houses the apparatus and is used to operate it. The dimensions, layout and details of the lab are shown in Figure 3-13.

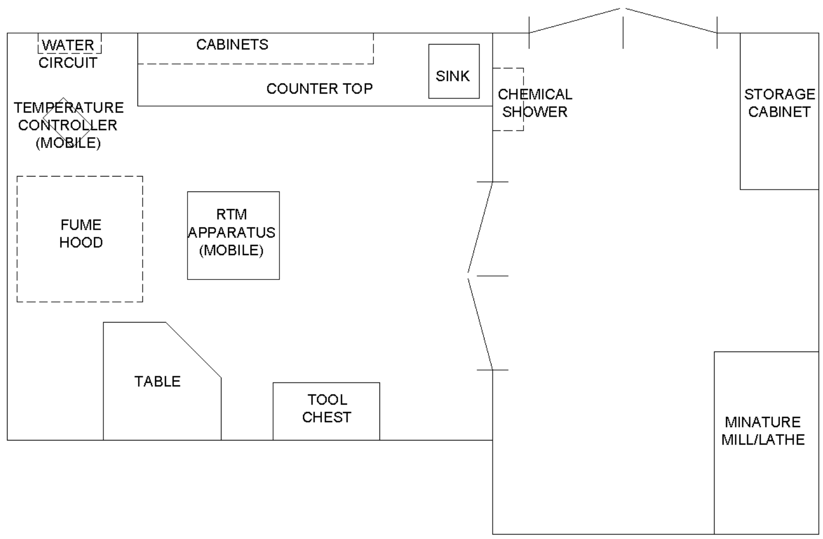

Figure 3-13: Layout of the laboratory

3.4.7.2 Tools and Equipment

To assemble, operate and maintain the apparatus certain tools and equipment must be on hand in the lab.

Naturally a set of standard hand tools is essential. These include sets of: pliers, vice grips, screw drivers, socket wrenches, open-end and box wrenches, adjustable wrenches, o-ring pics and mallets. A torque wrench is essential for assembly. Knives, drills and shears are always on hand.

A proper cutting tool to produce the preform is essential to producing an acceptable preform. Two tools are used in the lab, a hand held electric shear and a manually operated circular blade. The electric shears, shown in Figure 3-14 are the model: Workerbee made by Eastman Machine Company. The manual blade is simply an Olfa blade mounted in a block with a shaft and bearings.

Figure 3-14: Electric shears

3.4.7.3 Ventilation

A proper ventilation system is necessary in the lab to handle the fumes created by the chemicals used. To remove these chemicals a custom fume hood was installed and is shown in Figure 3-15.

Figure 3-15: Fume hood

The fume hood is made of galvanized steel, has a base of 4’ x 4’ and has integral florescent lights. A damper controls the airflow and a switch on the wall controls the fan motor.

3.4.7.4 Safety Equipment

When working with any chemicals it is important to read all applicable safety information and required by law to have MSDS (material safety data sheets) for each chemical on hand. Depending on regulatory bodies it may also be required to have a chemical shower. A chemical shower is located in the outer room as shown in Figure 3-13. Naturally eye protection, face shields, organic respirators, gloves and lab coats are essential. A first aid kit is mounted on the wall in front of the sink.

3.4.8 Assembly of System

Assembling the entire system can be broken down into assembling the mold and manipulating apparatus and assembling and connecting the external systems.

3.4.8.1 Assembly of Mold and Manipulating Apparatus

Assembly of the mold and manipulating apparatus begins with the table. Caster wheels are installed in the bottom of the table and adjusted to ensure that the table is level. The layer of plywood and insulation (that insulates the mold and levels out the table) and temperature control plate (with the integral piping installed) are placed on top of the table. The plate is screwed onto the table from the bottom. The mold plate is then placed on top and screwed onto the temperature control plate. Two locating dowels are screwed onto the top of the mold plate. These locate the two halves of the mold so that they align properly. The top plate is then placed onto the mold and the insulation and top frame is placed on the top plate. The top plate is screwed onto the frame. The lower half of the hinges are then bolted onto the back of the table and the upper half of the hinges are bolted onto the top frame. The hinge pins and limit stop pins are inserted. The clamps, hooks, mounting brackets and handles are then mounted onto the table and top frame. These are aligned using a square and the mounting screws and bolts are torqued to the appropriate magnitude with a torque wrench. The spring and spring arm are the remaining components to be installed. The spring arm is mounted onto the top frame and the top of the spring is mounted onto the arm. The other end of the spring is mounted onto the mounting bracket that is secured onto the table. To do this the mounting bracket must be loosened slightly and slid towards the back of the table. The top frame/top plate must be in the fully opened position. This gives enough room for the spring to be fastened to both the spring arm and mounting bracket. Once the spring is installed the mounting bracket can be tapped into place with a mallet and fully secured. This places tension on the spring so that when the mold is opened the spring is not in its fully retracted position as per the manufacturers recommendations. At this point the foam insulation may be placed in the top frame completing assembly of the mold and manipulating apparatus. This assembly requires at least two people and the use of a crane to manipulate the heavier components such as the plates and top frame.

3.4.8.2 Assembly of External Systems

With the mold and manipulating device fully assembled the external systems may be assembled and attached to complete the entire RTM apparatus. As previously mentioned the external systems consist of the injection device and injection valve, the catch pot and vacuum system, the temperature controller and the data acquisition system.

The pressure pot is connected to the injection valve with a standard quick-connect coupling. This allows for a very quick and easy connection/disconnection. The injection valve is fitted into the stainless steel insert in the mold and sealed by an o-ring on the valve. The valve is held in place with an aluminum bracket that has a screw to adjust and maintain the clamping force.

The catch pot is connected to the mold with standard ¼” polyethylene tubing. A stainless steel Swagelock vacuum fitting is mounted in the outlet port of the mold. This fitting connects and seals to the outside of the tube with an o-ring and is secured by a hand-tightened nut. The other end of the tube is fed into the same type of Swagelock fitting that is mounted on the top of the catch pot. The vacuum is connected to the catch pot with vacuum hose and a barbed fitting. It is important to apply an ample amount of vacuum grease to the hose and tubes before installing them in the fitting. This helps to insert the tube into the fitting as well as helps to prevent resin from curing in between the tube and fitting and bonding the tube to the fitting.

All water connections to and from the temperature controller are made with quick-connect couplings. There are two connections, one inlet and one outlet that connect the temperature control plate to the temperature controller. The temperature controller also has two connections from the 'wall', one for the water source and one for the drain.

The data acquisition system consists of five sensing units and an acquisition module. Three sensing units have a pressure transducer and thermocouple while the remaining two have just pressure transducers. These sensing units are mounted in the mold by means of a specially machined and threaded hole and tightened with a wrench. The sensors are connected to a 5 volt power supply and the data acquisition module. The data acquisition module is connected to a desktop PC with a USB cable.

3.4.9 Operation of system

Operating the system may be divided into three chronologically ordered tasks. First the mold must be setup, this includes hooking up all external systems and loading the preform. Once setup the mold is ready for injection, this includes mixing the resin and injecting it. Once the mold is filled the cure cycle starts, this includes controlling the temperature and removing the part from the mold.

3.4.9.1 Setting up mold

The mold takes roughly one to two hours to setup and requires a number of mutually exclusive tasks that can be done in any order. Before anything is setup it is a good idea to double check the operation of the injection valve and quick connect connections on the injection line. If not properly cleaned the valve may not operate and it is best to know this before the resin is mixed. Once this is in operating order there are three tasks to be completed: preparing the preform, preparing and loading the mold, preparing the injection system and preparing the outlet system.

Preparation of the preform is no trivial task. The quality of the preform has a very large dependence on racetracking and the quality of the finished component. If the preform is too small then excessive racetracking may occur which could result in dry spots. If the preform is too large the preform may not fit properly in the mold cavity causing it to protrude and become clamped between the two halves of the mold. This causes the mold to separate creating a path between the mold halves, again causing racetracking. The clamped fibers also damage the delicate surface of the mold. The preform for the panel is produced by cutting around a piece of aluminum sheet that acts as a template. The template is slightly undersized, once placed in the mold the fiber mat may be stretched slightly to meet the sides of the mold. The fiber is cut either manually with a circular razor blade or with electric rotary shears. The preform for the rectangular and semicircular sections involve preparing a foam core and the fiber. The wall thickness of the composite may be selected by adjusting the size of the foam core. For example if the desired thickness for the rectangular section is 1/8th of an inch and the mold cavity is 1.5" x 1.5", then the core must be 1.25" x 1.25". The rectangular foam core is produced with a knife and two straight edges to guide the blade. The semicircular foam core is machined to size on a router table and briefly sanded by hand to smooth down the cusps left by the router. Figure 3-16 shows the core being machined. Woven fiber cloth is then cut to size and wrapped around the core as shown in Figure 3-16.

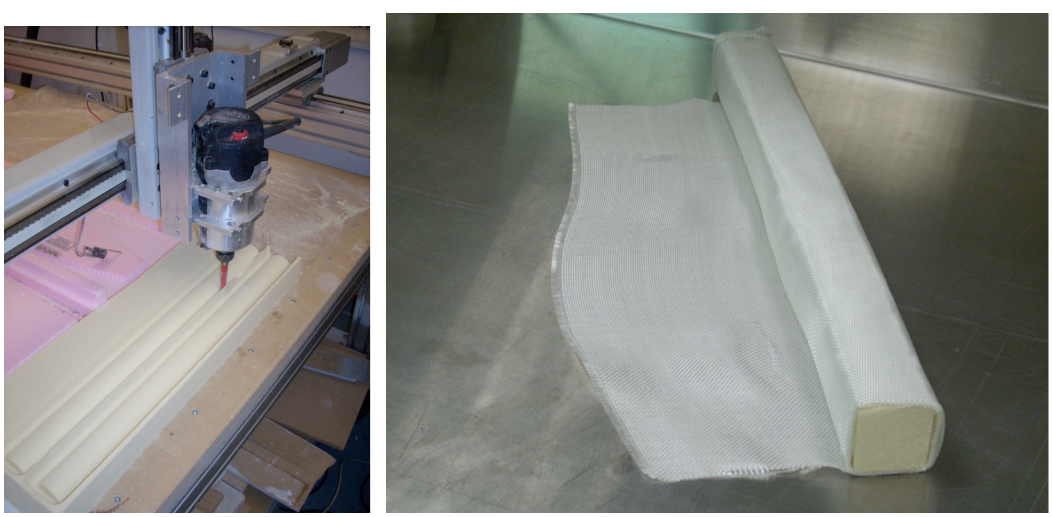

Figure 3-16: Machining semicircular core (left) and wrapping the rectangular core in cloth (right)

To prepare the mold a mold release agent must first be applied. The type of release agent depends on the resin used and the material that the mold is made from. After the release has had a chance to dry the fiber preform is loaded into the mold. Care must be taken when loading the mold to reduce the amount of distortion of the preform as it is very fragile and delicate. The preform should fit tightly in the mold so that it stays in place during injection and fills the cavity as well as possible. Once the preform is loaded the mold may be clamped shut. After clamped a vacuum should be applied to the mold to remove moisture from the mold and preform. This should be done directly before injection for about ten minutes.

The injection system is relatively straightforward to prepare. Assuming that the system is hooked up to the injection nozzle, all that is required is a pressure pot liner be cleaned with acetone and installed in the pressure pot. One or two small slits in the upper wall of the liner should be made to allow the air to equalize while the resin is being degassed in the pressure pot.

Preparing the outlet system simply requires installing a catch pot liner assuming the system is hooked up to the outlet ports of the mold.

3.4.9.2 Injection

Injecting the resin involves mixing the resin, degassing it, monitoring the filling and stopping it once complete. If an elevated mold temperature is required during injection the mold must be brought to the desired temperature before injection.

The resin must be mixed and placed in the pressure pot. This is usually done with a scale to obtain a higher accuracy. The mixing tolerance depends on the resin used; epoxy is often quite sensitive.

Once the resin is in the pressure pot a vacuum is applied to it for approximately ten minutes to degass the resin. Degassing helps to remove trapped air bubbles and moisture that accumulates in the resin while it is being shipped and sitting on the shelf waiting to be used.

Once degassed the resin is ready for injection. Depending on the injection technique a vacuum may be applied to the mold prior to injection to help remove air and moisture and increase the pressure gradient across the mold. If a pressure pot is used to inject then it is recommended to use nitrogen as the pressurizing gas since air contains moisture. The resin is injected until the mold is completely filled. Once full the outlet ports and injection port is closed off and the part is ready to be cured.

3.4.9.3 Curing, Removal and Post Processing

Curing and part removal is the least labor-intensive task. Curing is performed by following the resin manufacturer's time-temperature schedule. Once fully cured the part may be removed. This is done by unclamping the mold and removing the part. Sometimes the part may stick to the inlet/outlet ports. This is not a problem since these are attached to the flashing (extra resin around the part) and will be removed from the final part during post processing.

Post processing depends on the part that has been produced. It may involve simply cutting off the flashing and sanding the edges, sawing off the ends and removing a reusable core or dissolving a foam core with a solvent.

3.4.10 Specific operating parameters

This apparatus was designed to be operated under various conditions with a variety of molds and materials. The following section describes the specifics of the experiments.

3.4.10.1 Resin

The resin used in these experiments is RenInfusion 8601 made by Huntsman. A spec sheet is included in Appendix A. This resin was selected because of its extremely low viscosity and the fact that it is injected at room temperature. The mechanical properties of the resin were secondary. The resin was cured according to the manufacturer's recommendations, 24 hours at 25 °C and 6 hours at 66 °C.

3.4.10.2 Mold Release and Preparation

Before the mold was used the first time the mold was sanded and polished then sealed with AXEL XTEND WS-86m mold sealer and AXEL XTEND 818 mold release was applied. For sequential moldings only one or two coats was applied.

3.4.10.3 Reinforcement

Two types of reinforcement were used in the mold, common 6oz. plain weave E-glass cloth purchased locally and a special RTM reinforcement called Rovicore made by Cormorant. Rovicore is comprised of a porous polypropylene mesh sandwiched between two layers of random glass mat. The mesh helps resin flow through the fiber to saturate it.

Chapter 4 NUMERICAL SIMULATION

4.1 Introduction

As with any manufacturing technique the RTM method also has some important processing-related issues which will be elaborated in subsequent sections. These processing issues can be better understood and then addressed with the comprehensive knowledge of physical phenomenon taking place during the process. Therefore, mathematical modeling becomes an indispensable tool for accurate prediction of the parameters affecting the processing. The outcomes of the modeling study can be successfully used for the optimization of processing parameters and materials selection, and for the design of new molds. Modeling study will reduce cost and turn around time significantly.

For quality parts to be produced the reinforcement must be completely saturated with the matrix material. The matrix is injected and flows through the reinforcement until it reaches the outlet port(s). Naturally the matrix, like any fluid will take the path of least resistance, causing racetracking to occur. This means that unless the mold shape and placement of the inlet/outlet ports and process parameters such as pressure, resin viscosity, temperature, etc. is adequate there will not be a complete saturation of the reinforcement. Areas that are not fully saturated are known as void or dry spots. These areas render the part defective and often completely useless. The rate at which the flow progresses through the reinforcement is also of concern because two scales of flow occur simultaneously, macroscopic and microscopic flow, if these do not progress at the same rate then voids become trapped in the mold. Until more recently the shape and placement of the inlet/outlet ports and process parameters have been decided based on assumptions and experience. This can easily lead to an expensive mold that produces defective parts or even more serious, parts that appear to be fine but have major internal defects due to the inadequate filling process.

The degree of cure of the matrix plays a key role on the quality of the finished part. If the part is not allowed to fully cure the resin will not assume its desired properties. This can happen globally or locally. If the matrix is kept under temperature for too long precious time is wasted with no added benefit. Composite parts generally have internal stresses imposed during the curing of the matrix. This affects the strength and performance of the final part as well.

Aside from the mold filling, other aspects are also important to the engineer. Process cycle time is a major area of interest. If the cycle time can be reduced more parts can be produced in a lower amount of time therefore making the process more economical. Factors such as the mold filling time, resin rheology (the change of resin viscosity with time), cure time, temperature and preparation time all have an effect on the overall cycle time.

To overcome these aforementioned problems engineers have began to model virtually every aspect of the RTM process in attempt to analyze and design molds, optimize mold conditions and ultimately increase process efficiency. An accurate model takes much of the guesswork out of the process and ensures that high quality parts are produced efficiently.

This chapter presents a mathematical model for the simulation of the mold filling process in RTM process. For the modeling study, a multipurpose CFD software package (CFX) is used. A comparison of the experimental and computational results is presented in the next chapter. In order to investigate the effect of racetracking on the resin flow and mold filling, racetracking has also been incorporated into the developed model .

4.2 Issues influencing RTM

As mentioned above there are a number of key issues that effect the RTM process. These issues all play a key role in accurate modeling of the process. They will be discussed in further detail below.

4.2.1 Racetracking

Racetracking is a practical problem that has a enormous effect on the performance of RTM. It has a dependence on the fiber preform selection, injection strategies and mold stiffness. An accurate model of these effects not only influences the mold design but the preform size, type and handling methods.

Racetracking, often referred to as 'edge effects or 'edge flow' refers to the tendency for fluid to take the path of least resistance along the outer edges of the mold where the edge of the fiber preform meets the edge of the mold. This is physically caused by the fact that when fiber mat is cut the edges fray and have a different structure and therefore different permeability and fiber volume fraction than the bulk of the mat. In some cases it is difficult to size and align the fiber mat within the mold, gaps between the mat and mold add to this problem. In practice edge effects can never be completely eliminated, therefore an accurate model of this phenomenon is necessary to effectively analyze the mold filling process.

To model edge effects many researchers have suggested the use of a higher value of permeability at the edges in question. Hammami, et al [17] have proposed two models based on geometric factors for the permeability at the edge of the mold. The first model is derived from the Navier-Stokes equation in an assumed channel between the fiber edge and mold. Without derivation the expression is presented in equation (4-1), where d is the channel width.

$$k = \frac{d^2}{12} \qquad \text{Eqn(4-1)}$$

Another expression assumes flow takes place in a cylindrical channel as in Poiseuille flow. This model takes into account cavity thickness, *h* and channel size, *d.* It is represented in equation (4-2)

$$k = \frac{hd}{8\pi} \qquad \text{Eqn(4-2)}$$

After experimentation it was noticed that transverse flow from advanced racetracking has a strong effect on the flow pattern. Transverse flow is flow from the outer edge where the preferential flow has advanced into the middle of the preform, ie. flow 90° to the expected flow front. It was proposed to incorporate this phenomenon into a finite element method (FEM) implementation by considering a sub-region that consists of the outer edge and a portion of the fiber rather than considering the outer edge as a region separate from the fiber domain. By using this sub-region the permeability can be incorporated directly by simply modifying the permeability tensor. A proposed model for the permeability of the sub-domain is shown in equation (4-3).

$$k_t = k\frac{d}{l} + k_y\frac{(1-d)}{l} \qquad \text{Eqn(4-3)}$$

Where, k is one of the two previously presented models and k_y is the permeability of the reinforcement in the transverse direction and *l* is the width of the area sub-region.

After experimentation it was also confirmed that each permeability model performed best for different ranges of channel width. For channel widths from 2/3h to 3/2h the model presented in equation (4-2) was more accurate while the alternative model was better for the remaining channel widths (equation (4-1)).

4.2.2 Fiber deformation

Fiber deformation occurs when the flow of resin through the fiber reinforcement deforms the fibers and shifts their position. Washout is an extreme case of fiber deformation that occurs when the matrix flow pushes the fiber through the mold rather than flowing through the fiber. Fiber deformation leads to areas that have lower fiber fractions and displaces the fibers such that the molded part has different flexural characteristics. This phenomenon depends on parameters such as porosity and permeability of the reinforcement, reinforcement stacking sequence, fit of the reinforcement in the mold, stiffness of the mold, matrix flow rate and matrix viscosity. All of these parameters must be considered when modeling the mold filling process. Researchers such as Han et [12] al Hammami, Gauvin, and Trochu [17] have studied these issues.

4.2.3 Macroscopic and macroscopic flow

A wide variety of materials such as glass, carbon, aramid, boron and organic materials like hemp and flax are used in RTM. There are also a wide variety of fiber arrangements and orientations. Initially each fiber is made as a single strand with a diameter on the order of micrometers. Once the initial strand is made it may be used in a variety of arrangements such as woven mat, random mat, unidirectional mat, rope, whiskers or particles. The common types of reinforcement used in RTM are woven, random and unidirectional mat. In all of these arrangements individual fibers are gathered together to create larger strands called tows, rovings or bundles. Essentially a tow, roving or bundle is hundreds of fibers grouped together with their axes parallel to each other. These tows are woven together to create a mat in a manner very similar to common textile fabrics.

Understanding the manner in which the fiber reinforcement is oriented is important when modeling the flow through it. Two scales of flow occur simultaneously, macroscopic and microscopic flow. Macroscopic flow is when the fluid travels between the fiber bundles and microscopic flow is when the fluid travels within the fiber bundles around the individual strands of fiber. Macroscopic flow leads to mold filling while microscopic flow leads to fiber impregnation. Macroscopic flow is governed by the pressure gradient across the mold while microscopic flow is governed by capillary pressure, which is dependent on surface tension. If these two flow fronts do not proceed simultaneously then the mold will fill before the fiber is fully saturated creating microscopic dry spots.

The microscopic flow is dominated by capillary pressure. K. Potter [12] has proposed a model of the capillary pressure, p_c as shown in Equation (4-4).

$$\Delta p_c = \frac{\gamma \cos\theta}{r} \frac{2V_f}{1 - V_f} \qquad \text{Eqn(4-4)}$$

Where V_f, γ and r are the fiber volume fraction, resin surface tension and radius of channels between the fibers and θ is the contact angle between the fiber and resin flow front.

To assist the microscopic flow in any given fiber arrangement three techniques may be employed:

1. A chemical referred to as 'sizing' that reduces the surface tension of the fibers may be applied.
2. A chemical referred to as 'surfactant' that reduces the surface tension of the matrix may be added.
3. An air venting strategy may be employed. This is usually done by putting the mold under a vacuum during the injection process. This is an important option to consider when one is modeling the filling process.

The addition of sizing and surfactant affect the magnitude of γ in equation (4-4) while the venting strategy helps to physically remove the air that may be trapped within the fiber strands.

With an accurate model of the macroscopic and microscopic flow the molding parameters may be optimized to allow both flows to proceed at the same time thus reducing the overall cycle time. Many researchers such as Patel and Lee Hayward and Harris and Chen among others have studied this problem [12].

4.2.4 Cycle time

Using traditional materials and methods RTM has a cycle time on the order of 1-3 days. Without automated equipment producing the preform, preparing the mold and preparing the resin are time consuming and labor intensive procedures. The cure time of many resins used for matrix are on the order of 24-48 hours. These issues have relegated RTM to low volume production. Major auto manufacturers are looking to improve the turn around time of RTM so that it is capable of producing parts on the order of 100 000 per year [12].

The process can be divided into two parts: (i) open mold operations such as cleaning and preparing the mold and (ii) closed mold operations such as mold filling and curing. Much attention has been paid to the mold filling process however that only takes a fraction of the overall cycle time.

One major influence is the cure time of the matrix. Cure depends on part thickness and the amount of material occupying a region. Different strategies have been proposed to improve the cure time and make it more uniform. One method proposed is phased catalyst RTM [12] where the reaction rates vary across the mold depending on the catalyst and amount injected in these areas. The objective of this method is to make all areas of the part to cure at the same time therefore eliminating any areas that require more cure time than other areas thereby increasing the overall cure time. An accurate model of the cure which models the chemical reaction rate, exothermic heat generation and the heat produced and dissipated by the mold would allow for this technique to become feasible.

4.3 The State of the Art and Solution Techniques

There are a multitude of techniques and issues in use to model the RTM filling. Models that include heat transfer, cure dynamics and internal stress have been proposed. A variety of techniques to model these phenomenon are available as well. Much work is being done on formulating an analytical expression for the porosity of the reinforcement. This is currently an empirically obtained technique.

4.3.1 The State of the Art

As mentioned there are many aspects of RTM such as mold filling, curing, cycle time, edge effects, fibre deformation and permeability that are modeled.

The state of the art for modeling the mold filling process lies in non-isothermal models that incorporate heat transfer between the resin, reinforcement and mold, heat generation from the exothermic reaction of the resin during cure, energy convection by the flow and rheological change in the fluid as the reaction proceeds and heat is transferred to and from the fluid. Examples of such models are presented by Abbassi, A. et al [11], A., Ghaffarian, S.R. et al [12], Henz, B.J et al [14], Henne, M. et al [18] and Yoo, Y. et al [21] among many others. Researchers such as N., Lawrence et al [23] present a model for resin viscosity.

The question of modeling resin as a Newtonian fluid has come up among researchers. Since the vast majority of models use Darcy's law to model flow through the porous reinforcement a Newtonian fluid is implied since Darcy's law is a linear relationship between velocity and viscosity. Many researchers do not address the assumptions used to justify the use of a Newtonian fluid, they simply justify the use of Darcy's law. The assumptions that justify Darcy's law when derived from the Navier-Stokes equation are bulk and dispersive inertia effects are negligible and viscous force is ignored. Relying on the order of magnitude analysis, Tucker and Dessenberger [11] have indicated that these assumptions are valid for all RTM processes. Advani, Suresh G. et al [37] state that most thermoset resins (the most commonly used resins for RTM) may be considered a Newtonian fluid however as the thermoset resin begins to cure this may not remain true. Many researchers including Fracchia, Tucker and Gebart et al [20] report that the experimental results correlate with their Newtonian fluid based models. However, Gauvin and Chibani report experimental results where the flow is not linearly dependent on the pressure gradient, basing this result on the assumption that the Resin is not Newtonian

[20]. Bruschke and Advani have included a non-Newtonian viscosity model based on Power Law and Ellis model that has been incorporated into Darcy's law [12]. Despite these reported discrepancies the majority of state of the art models use Darcy's law treating the resin as a Newtonian fluid [11].

Models that address the flow on both microscopic and macroscopic scales are also being presented. Examples of such models have been proposed by researchers such as: Wang, Bai-Chen et al [24] and Binetruy, C. et al [25] and have been studied experimentally by V. Rohatgi, et al [29] among others.

State of the art modeling of the curing stage involves modeling the chemical reaction of the fluid as a function of time and temperature and modeling the internal stresses in the finished part as a function the shape and cure history. The cure reaction is accelerated by heat; areas that have a larger volume develop more heat and cure faster than thin regions where the temperature is dissipated quicker. The state of the art includes models that incorporate mold shape, heat production and dissipation of the part and internal stress in the final product. Researchers such as Lombardi, A. V. [26], Ruiz, E. et al [27] and N. Pantelelis, et al [28] have worked to develop models of the cure.

A numerical model of the permeability of the reinforcement is useful to estimate the permeability values that will be used in the model. Generally this value is found empirically or if less critical estimated to be within a certain range. The permeability is a function of the fiber size, fiber geometry and fiber volume fraction. A heuristic model presented by Gutowski et al [20] is given in equation 4-5.

$$K = \frac{R^2}{4k'}\frac{\left(\sqrt{\frac{V_a'}{V_f}}-1\right)^3}{\left(\frac{V_a'}{V_f}+1\right)} \qquad \text{Eqn(4-5)}$$

Where *R* is characteristic fiber radius and V_a' and *k'* are empirical parameters. The weakness of this model is the need for empirical parameters. B.R. Gebart [20] proposes a model to estimate the permeability that is derived from fiber geometry. The first model predicts permeability for flow perpendicular to the fibers, it is shown in equation 4-6 for hexagonally aligned fiber.

$$K_{perp} = \frac{16}{9\pi\sqrt{6}}\left(\sqrt{\frac{\pi/\left(2\sqrt{3}\right)}{V_f}} - 1\right)^{\frac{5}{2}} R^2 \qquad \text{Eqn(4-6)}$$

The second model, shown in equation 4-7 predicts the permeability for flow parallel to the fibers.

$$K_{par} = \frac{8R^2}{c}\frac{\left(1 - V_f\right)^3}{V_f^{\,2}} \qquad \text{Eqn(4-7)}$$

Where c is a shape factor based on the fiber size and arrangement.

4.3.2 Solution Techniques

Methods commonly used to solve the filling process include the finite difference method (FDM), the boundary element method (BEM), the finite element method (FEM), the control volume/finite element method (CV/FEM) and smoothed particle hydrodynamics method (SPH). However most of these methods present a problem when simulating mold filling due to the moving boundary between the fluid and air. The treatment of the moving boundary is an important problem; it is not trivial.

There are two approaches to solving these problems. The first involves a moving grid where the area that the resin occupies must be re-meshed on each time step. This method requires more computational resources and time than a simulation with a fixed grid and no moving boundary. The second approach uses a fixed grid which is meshed only once in the beginning of the solution. With this method another algorithm must be employed to track the interface. The moving grid approach can give a more accurate representation of the flow front however it runs into problems when flow fronts merge such as with flow around an obstacle or multiple injection sites. Because of these difficulties the fixed grid approach has won favor and is more commonly used.

The FDM is relatively easily implemented for simple 2-D geometries; however implementation of more complex boundaries becomes more difficult and complex. The BEM has the advantage of reduced mesh generation however conservation of mass is not always maintained when the flow front meets the walls. Both of these methods are based on a moving boundary approach.

The BEM uses a mesh on the outer surface of the domain rather than through the entire volume. BEM calculated boundary conditions for the mesh in the post-processing stage and attempts to interpolate the boundary conditions to the interior points of the volume. This method is good for cases that have a small surface/volume ratio (such as in RTM) however the solution method creates a fully populated matrix, which is more computationally expensive to solve, compared to the banded matrix constructed in the FEM method.

SPH is an alternative method that unlike the previously mentioned methods does not require a mesh. SPH discretizes the fluid into a number of interpolation points commonly referred to as particles. Each particle is tracked individually; an averaging technique is used to gather data from neighboring particles to calculate the properties of the particle in question. SPH is particularly suitable to molding simulations since there are no issues associated with flow front tracking as it is inherently built into the technique. This method is relatively new and there are still many issues to be worked out before it may receive widespread use. Comas-Cardona, S. et al [22] present a solution method which uses a combination of FE and SPH. The control volume/finite element method (CV/FEM) appears to be the most efficient technique for simulation [12]. It has no limitations on merging flow fronts and does not require re-meshing at each step. This method does however require a method of tracking the flow front. The volume of fluid (VOF) approach is commonly used in this case and will be discussed in more detail in the following sections.

In the CV/FEM method, each control volume (CV) is created by subdividing each element of the original mesh. The control volume then consists of subdivisions of each neighboring element centered on a node. This control volume is used to plot the flow front based on the tracking method. In the case of the VOF method a value indicating the amount of fluid in the CV and direction normal to the flow front is calculated for each node. This information is used to plot a line indicating the flow front that intersects the CV.

4.4 Numerical Model

As previously mentioned a model of the mold filling process has been implemented with a commercially available multipurpose software package, ANSYS 10.0. This model attempts to predict an isothermal mold filling process with edge effects.

In this model the flow in the mold is modeled as homogeneous multiphase flow through a porous domain. The flow is multiphase, meaning there are two distinct phases, resin and air. Initially the mold is filled with air, as the resin flows through the porosities in the fiber the air is forced out of the mold. Tracking the free surface or flow front is also of importance and will be discussed. A method known as the volume of fluid method is used to track the free surface. The mold is modeled as a porous domain governed by Darcy's law. As reported by A. Shojaei, et al [12] all researchers have treated the modeling of mold filling stage by using the theory of flow through a porous media and almost all flow models used to model the filling process are based on Darcy's law as a governing momentum equation. This law is an accurate assumption because the reinforcement material acts like a porous medium. Most models of the RTM process consider the fluid to be Newtonian [12] with the noted exception of Bruschke and Advani [12] who have used a non-Newtonian viscosity model. This model assumes Newtonian fluid. The following sections briefly describe the methods used to solve the mold filling process.

4.4.1 Flow in Porous Media

The porous domain is modeled using Darcy's law as a governing momentum equation. This is an empirical formula that relates the fluid velocity, fluid viscosity, media porosity and pressure drop. The law was formulated by Henry Darcy in the 19th century and is analogous to Fourier's law of heat conduction and Ohm's law.

In 3-D, Darcy's law can be expressed as shown in equation (4-8) where V_x, V_y and V_z are the velocity components in the *x, y* and *z* directions respectively, K_{ij} is the second-rank permeability tensor, *g* is gravity in the direction specified by the subscript, *p* is the pressure, ρ is the fluid density and η is the viscosity. In RTM the viscosity is generally in the range of 0.2 to 1 Pa-s [12] however this depends on the matrix used and the mold and resin temperatures.

$$\begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = -\frac{1}{\eta}\begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix}\begin{bmatrix} \frac{\partial p}{\partial x} - \rho g_x \\ \frac{\partial p}{\partial y} - \rho g_y \\ \frac{\partial p}{\partial z} - \rho g_z \end{bmatrix} \qquad \text{Eqn(4-8)}$$

Presented in tensor notation this expression takes on the form shown in equation (4-9).

$$\vec{V} = -\frac{\overline{\overline{K}}}{\eta}(\nabla p - \rho\vec{g}) \qquad \text{Eqn(4-9)}$$

where $\vec{V}$ is the velocity vector, and $\overline{\overline{K}}$ is the second-rank permeability tensor. Another important concept related to flow in porous media is porosity. Porosity is the ratio of the empty volume within the medium where fluid can flow to the total volume of the medium. Porosity is a fraction between 0 and 1 where 0 represents a completely solid medium and 1 represents an empty medium with no solid present. Equation 4-10 is used to define porosity, ϕ.

$$\phi = \frac{V_v}{V_T} \qquad \text{Eqn(4-10)}$$

Where V_v is the volume of the void space and V_T is the total or bulk volume of the material.

4.4.2 Homogeneous Multiphase Flow

In the homogeneous multiphase flow model, a common flow field, temperature field and other relevant fields are shared by each fluid. This is the distinct difference compared to the alternative inhomogeneous model available in ANSYS CFX. Since these assumptions are held, certain simplifications can be made and shared fields can be solved rather than solving individual transport equations for each phase. This results in a simpler and less computationally expensive model at the expensive of accuracy. The homogeneous model is valid (among other circumstances) for: "A free surface flow where the interface is well defined. In this case, the volume fractions of the phases are equal to one or zero everywhere except at the phase boundaries and it makes sense to use a single velocity field" [15],[16].

4.4.3 Interface Tracking

The interface between the two fluids is tracked using the 'Volume of Fluid' method. This method utilizes a 'color function', C that has a value of 1 when the cell in question is fully saturated and 0 when empty. The average value of this function inside a cell represents the fraction of volume that is filled. Since the value is not entirely saturated these cells must contain a free surface. Once it is known that a free surface lies in a given cell the orientation of the surface must be determined. The direction normal to the boundary lies in the direction in which the color function changes most rapidly. The derivatives of the function can then be used to calculate the normal direction. Care must be taken when calculating these derivatives since the function is a step function. Once the normal direction and the value of the color function in a boundary cell are known, a line approximating the interface can be constructed. This boundary can be plotted for each cell and will interpret the free surface [19].

The evolution of the color function is governed by equation 4-11.

$$\frac{\partial C}{\partial t} + \nabla \cdot \left(\vec{V} C \right) = 0 \qquad \text{Eqn(4-11)}$$

Where C is the color field function and $\vec{V}$ is the fluid velocity.

4.4.4 Governing Equations and Solution Method

ANSYS CFX 10.0 uses a slightly modified version of Darcy's law to model flow in porous media. The equations for conservation of mass and momentum are shown using the symbols and notation presented in the ANSYS text [15], [16] in equations 4-12 and 4-13 respectively.

$$\frac{\partial}{\partial t}\gamma\rho + \nabla\cdot\left(\rho\overline{\overline{K}}\cdot\vec{U}\right) = 0 \qquad \text{Eqn(4-12)}$$

$$\frac{\partial}{\partial t}\left(\gamma\rho\vec{U}\right) + \nabla\cdot\left(\rho\left(\overline{\overline{K}}\cdot\vec{U}\right)\otimes\vec{U}\right) - \nabla\cdot\left(\mu_e\overline{\overline{K}}\cdot\left(\nabla\vec{U} + \left(\nabla\vec{U}\right)^T\right)\right) = -\gamma\overline{\overline{R}}\cdot\vec{U} - \gamma\nabla p$$

Eqn(4-13)

Where $\vec{U}$ is the true velocity, μ_e is the effective viscosity which is a combination of the viscosity of the two phases based on the value of the color function in the region, γ is the volume porosity, A is the area porosity, ρ is the density of the fluid and $\overline{\overline{R}}$ represents a resistance to flow in a porous medium (and is a positive definite second rank tensor in order to account for possible anisotropies).

Since a large resistance is present in porous medium flow, a large pressure gradient must be present to balance the resistance, therefore the terms on the right hand side of equation 4-13 are large (and of opposite sign) while the convective and diffusive terms on the left hand side of equation 4-13 are small. These terms may be neglected resulting in a simplified version of equation 4-13 shown in equation 4-14.

$$U = -\overline{\overline{R}}^{-1}\cdot\nabla p \qquad \text{Eqn(4-14)}$$

This equation is very similar to that presented in equation 4-9 however the gravity terms have been neglected, the permeability term, $\frac{\overline{\overline{K}}}{\eta}$ has been replaced with $\frac{1}{\overline{\overline{R}}}$ and the velocity term $\vec{U}$ is the actual velocity (which is discontinuous at discontinuity in porosity) rather than the averaged superficial velocity typically used in Darcy's law.

If the flow is assumed to be incompressible then $\vec{U}$ will be divergence free ($\nabla \cdot U = 0$). If we take the divergence of equation 4-14 assuming the flow is incompressible we arrive at equation 4-15 as follows [15], [16].

$$\nabla U = \nabla(-R^{-1} \cdot \nabla p) = 0 \qquad \text{Eqn(4-15)}$$

Assuming $\overline{\overline{R}}$ is an isotropic medium we get equation 4-16.

$$\nabla^2 p = 0 \qquad \text{Eqn(4-16)}$$

We now have all the equations necessary to obtain a solution. The solution method is represented in the block diagram in Figure 4-1. The solution procedure starts by using the initial conditions to solve for the pressure gradient across the entire domain with (4-16). Using the pressure data, the velocity is solved for using (4-14). With the velocity data, the color function can be solved for with (4-11). This represents the flow front position using the volume of fluid method. The interface direction can then be found by calculating the normal to the boundary by calculating the direction in which *C* changes most rapidly. For regions where *C*=0 set the velocity in that region to zero. This process is repeated until the desired number of time steps is completed.

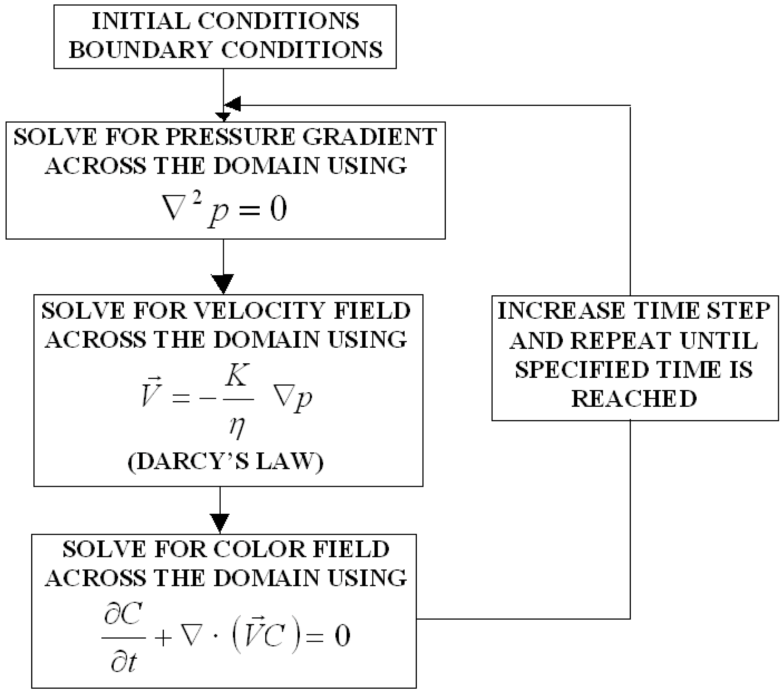

Figure 4-1: Solution Method

Since a homogeneous flow model is used, flow fields for both fluids are solved at the same time using the above algorithm. To make this possible the value of viscosity that is used in the Darcy's law equation must change depending on the fluid that fills the area being calculated. For example, if the area is filled with resin, then the resin viscosity value must be used and when the area is filled with air, a viscosity value for air must be used. This is made possible by equation 4-17, which represents a value of viscosity depending on the color function.

$$\eta = \eta_{resin} C + \eta_{air} (1 - C) \qquad \text{Eqn(4-17)}$$

At the interface the value of *C* is neither unity nor zero and therefore equation 4-17 give an average or 'effective' viscosity for that region.

4.4.5 Computational Domain

As mentioned previously the domain is based on the quasi 2-D experimental mold. The mold measures 12” x 24” x 0.13” and has one injection site and two outlet sites as shown in Figure 4-2.

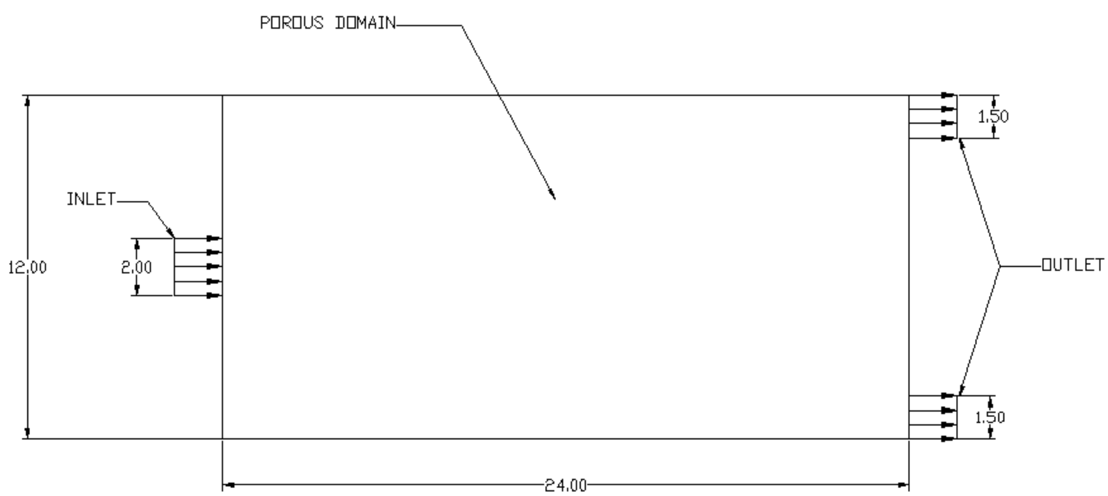

Figure 4-2: Computational domain

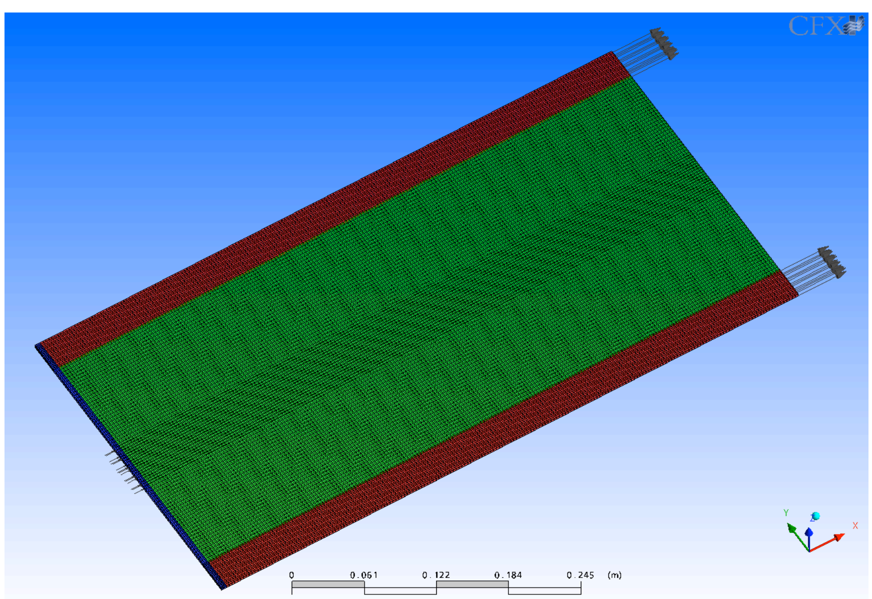

Figure 4-3: Mesh for simulation

To model edge effects many researchers have suggested the use of a higher value of permeability at the edges in question. Hammami, et al [17] have proposed two models based on geometric factors for the permeability at the edge of the mold. Another expression assumes flow takes place in a cylindrical channel as in Poiseuille flow.

The mesh of the domain is shown in Figure 4-3. In this model, race tracking is incorporated on the outer edges along the length of the mold by varying the values for permeability and porosity (fibre volume fraction) according to respective functions. These areas are indicated in red in Figure 4-3. This produced realistic results once the simulation was half way through however until then there was much discrepancy with the experimental results. Visual inspection of the fluid flow during the experiment suggests that there is also a race-track that runs along the edge where the fluid is injected. Once removed from the mold the specimen suggests that there is a small amount of fibre deformation along this edge as the resin pushes the fibres at the leading edge into the perform, creating a channel-region with little to no fibre. To account for this a small, non-porous region was placed along the edge where the fluid is injected. This area is shown in blue in Figure 4-3. This produces results that coincide quite closely with the experimental results. The mesh density can also be seen in Figure 4-3. The mesh is denser in the middle of the mold. A blocking strategy was used to control the mesh density.

4.5 Boundary and Initial Conditions

There are three types of boundary conditions (bc's) used in this model. The majority of the boundaries of the domain utilize a no-slip boundary condition. There is also one inlet and two outlet bc's described in Figure 4-2.

The majority of the boundaries of the domain are boundaries between the fluid domain and a solid surface, often referred to as a solid surface boundary condition. Three options are available for this b.c., no slip, partial slip and free slip. These can be expressed mathematically in the x direction using equation 4-18.

$$u_x = -\beta\tau_{xy} \qquad \text{Eqn(4-18)}$$

Where u_x is the velocity, τ_{xy} is the shear stress and β represents the amount of slip. If $\beta = 0$ then a no-slip condition would be in place, if β is a non-zero value a partial slip condition is in place and as β approaches ∞ a free slip condition is approached because τ_{xy} approaches 0.

There is also a no-flow condition on these areas since the fluid does not flow out of the surface. This can be expressed mathematically using equation 4-19.

$$u_n = 0 \qquad \text{Eqn(4-19)}$$

Where *n* is the direction normal to the wall.

For this model a free slip condition is used. One reference, [21] justified the use of this model because the pore size of the fiber preform is much smaller than the characteristic mold length making the no-slip boundary condition applicable.

The inlet boundary condition is in place at the resin injection site. The magnitude and direction of the inlet velocity is specified. The direction of the inlet flow is normal to the edge of the boundary surface. This models the real life injection conditions when a resin pump is used. An alternative inlet condition that could be employed is a pressure specified bc. This is when the magnitude of the pressure is specified and would simulate injection with a pressure pot, another commonly used injection device that maintains a constant injection pressure with a variable injection velocity.

The outlet boundary condition is in place at the two vents or outlet ports. The relative static pressure is specified, in this case atmospheric pressure. This would simulate the real life conditions felt during the molding process. It is common to apply a vacuum to the outlet of molds. This condition would be implemented by simply specifying the appropriate outlet pressure.

The initial conditions for this problem lie in three fields, the pressure field, the velocity field and the color field (as described in equation 4-11). The pressure field is set to atmospheric (or outlet pressure) over the entire domain, the velocity field is set to zero over the entire domain except at the inlet where it is set to the specified inlet velocity, the color field is set to zero across the entire domain except at the inlet where it is set to 1 to indicate the presence of fluid.

Obtaining convergence with a transient simulation is not trivial. It depends on a parameter known as the Courant number, $C = V(\Delta t / \Delta x)$ where V is the magnitude of fluid velocity, Δt is the time step size and Δx is the mesh spacing. For convergence the Courant number should be as close to one as possible. If it is greater than one the solution may not converge and if it is less than one the solution is less efficient. There are three variables that can be modified to make the Courant number equal to one. The mesh size and time step can be explicitly controlled with the software settings while the velocity can only be implicitly controlled and is a function of the inlet velocity/flow rate, geometry, permeability and porosity. The solver manager in CFX outputs the maximum Courant number across the entire domain and outputs the residual values indicating whether or not convergence has been met. To maintain a Courant number close to 1, an adaptive time step has been selected.

Chapter 5 RESULTS AND DISCUSSION

5.1 Introduction

The main focus of this study is to establish an advanced composite research laboratory with the capability of manufacturing polymer-based advanced composite materials mainly for aircraft by the RTM method. In this direction, a fully operational laboratory scale RTM apparatus with the flexibility of manufacturing composite structures with 2- and 3-D geometries has been designed, built and tested. The RTM apparatus was designed such that it enables us to study RTM processing parameters that have significant effects on the quality of the manufactured components such as resin flow through porous medium, and race tracking. Visual monitoring of the process has been performed by means of the visualization window as described in the body of the thesis. A video camera has been setup above the mold to record the mold during filling. The facility developed within the framework of this research program will also be a very valuable infrastructure to produce composite structures with embedded fiber optic sensors for structural health monitoring and damage prognosis in our future research in this field.

5.2 RTM Apparatus Operation

Once the design, manufacture and assembly stages are complete the apparatus must be tested and possibly modified so that the mold will operate successfully and can be used for experimentation. The quasi-2D mold was the first to be tested and experimented with; once experiments were complete the 3D mold was tested and used for experimentation

5.2.1 Quasi-2D Mold Operation

Successful operation of the quasi 2D molding apparatus has been achieved after some trial and error. Figure 5-1 shows images of the produced moldings. The image on the right is included in an attempt to demonstrate the quality of the panel. The word 'panel' is written on a piece of paper and placed beneath the panel. The text is clearly visible and there are no trapped air bubbles or contamination in the panel.

Figure 5-1: Successfully molded panels

Two major issues were faced during the initial test runs with the quasi-2D mold. The most critical was finding a suitable mold release agent. A readily available, low cost high temperature carnauba wax/silicon commonly used in composite molding was used on the first run. After the part was cured on the first run the mold would not open. A crane was used in an attempt to open the mold, however this simply lifted the mold off the ground rather than opening it. Eventually a heavy-duty pry bar was used to separate the mold. This ripped the glass-viewing window out of the top plate leaving the shattered remains of the glass window bonded to the top of the panel and the panel bonded into the mold cavity as shown in Figure 5-2 (right). With minor damage to the mold the panel was eventually pried out with a flat wooden stick. Figure 5-2 (left) shows the removed panel.

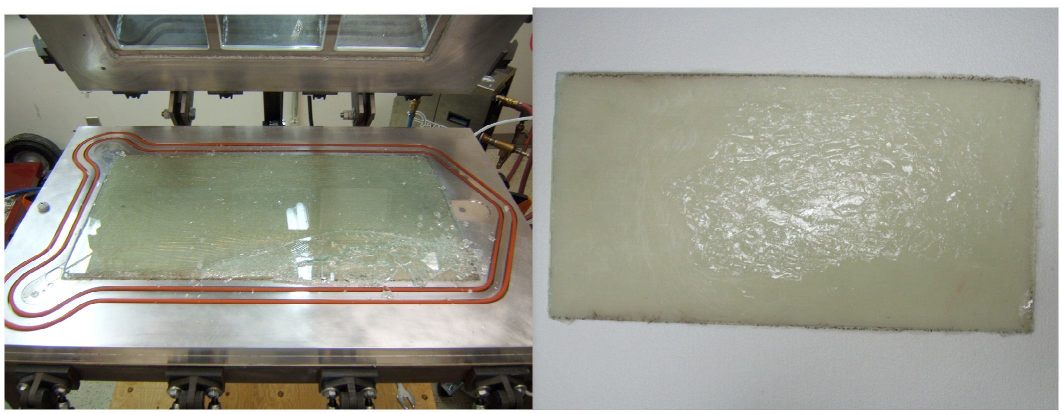

Figure 5-2: Panel with glass viewing window bonded to it

The second issue faced during the first test run was the amount of resin that was required to be mixed and injected. It is not a simply a case of calculating the volume of the mold and inlet tubes; there must also be excess resin that is allowed to exit the mold during injection to remove trapped air. There was not enough resin for the first run, which caused air to be injected into the system. Through trial and error the acceptable amount of resin to be mixed was determined.

5.2.2 3D Mold Operation

There were two main issues to overcome with the 3D mold. These were removing the component from the mold and finding compatible constituent materials, since a foam core was used.

The same successful mold preparation and mold release agent that were used with the quasi-2D mold were used in the 3D mold however the molded component still had demolding problems. The main geometric difference between the two molds is the vertical surface area. There is considerably more vertical surface area on the square section in the 3D mold, roughly seven times more. This is the region that has trouble releasing despite the fact that there is a 5° taper. To remove the component pry-bars were inserted into the component and used to pop it out. This technique was successful however portions of the component were damaged by the pry-bar. The semicircular section released more easily, however a prybar was still used.

Figure 5-3: Molded bar with dissolved core

A polystyrene foam core was used in the first 3D molding. When removed, it was clearly visible that the foam had been dissolved by the epoxy. Figure 5-3 shows the dissolved core; bubbles that formed during the reaction rose to the top of the bar. A polyurethane foam core was used on the second molding. When removed, the core appeared to be intact however it had shrunk slightly and the end near the injection port appeared to be dissolved. On the third molding a polystyrene core sealed with white glue was used.

Upon initial inspection it appeared that the sealing prevented the foam from being dissolved however a closer inspection revealed that the surface of the foam had been dissolved slightly. A polyurethane core was used once again and appeared to be compatible during the mold filling process. During cleaning of the injection nozzle it was noticed, by accident that acetone was being injected into the mold due to a leaky seal in the nozzle. The acetone being injected under high pressure was what dissolved the polyurethane core in the previous attempt and not the resin as originally thought. Subsequent moldings have proven this to be true. The polystyrene foam however, does react with the epoxy. As a rule of thumb, epoxy resin does not react with any type of foam and polyurethane does not react with any type of resin. Since this resin is made specifically for RTM applications styrene is added to the resin to reduce the viscosity and it is the styrene that reacts with the polystyrene foam.

Once the initial problems were overcome, successful specimens were produced as shown in Figure 5-4.

Figure 5-4: Examples of 3D components

5.3 Results

While one of the focuses of this work was to study racetracking some other issues came up during experimentation that are worth mentioning. Each RTM mold has different characteristics and performance. The issues associated with each mold were much different.

5.3.1 Quasi-2D Mold

A pressure pot was used to inject the resin into the mold. Nitrogen was the pressurizing gas used for injection. The injection pressure varied from roughly 5 to 35 psi depending on the mold and reinforcement. A vacuum was applied to the outlet of the mold adding roughly 14 psi to the pressure gradient.

The time to fill the mold was roughly 25 minutes. The actual time for each experiment with the same resin and resin/mold temperature, depended on the injection pressure and the extent at which racetracking took place.

Two types of reinforcement were used, Rovicore by Cormorant and 18 layers of 6oz. plain weave E-glass cloth. The Rovicore was much more permeable compared to the woven cloth. The resin used was RenInfusion 8601 epoxy, the spec sheet is included in Appendix A. The resin was cured by holding it at 25 °C for 24 hours then 66°C for 6 hours.

5.3.1.1 Racetracking

The most obvious outcome of these experiments is confirmation of the relatively random nature of racetracking. The experiments show that there is a very high dependence on producing, handling and loading the preform since no two experiments produced the same racetracking pattern. This could be likened to the butterfly effect where a seemingly insignificant factor has a huge effect on the final outcome.

A general racetracking pattern reoccurred and is shown in Figure 5-6. In some experiments this pattern would occur on both sides, sometimes on just one and sometimes not at all. The reason that this shape occurred was due to two factors. Rather than injecting radially outward from the injection port as initially expected the mold seemed to inject from a line source where the flow front in the middle of the mold progressed in a straight line rather than a curved flow front. After visual inspection of a number of specimens it was noticed that the resin compressed the front edge of the preform and created a channel with very little fiber, a racetrack. In an attempt to avoid racetracking due to undersized fabric preforms, oversized preforms were produced and loaded into the mold. Rather than eliminating racetracking this attempt actually made it worse because the outer edges of the preform got clamped outside of the mold cavity in between the two mold halves causing separation of the mold and producing a channel with very little resistance to flow. The interesting thing about this type of racetracking in this apparatus is that it was not visible because the viewing window ends at the edge of the mold. This caused much confusion when there was resin exiting the mold while it appeared that the mold was only one third filled. After removing the panel however it was noticed by visual inspection that fibers were on the outer areas of the mold cavity. These fibers also left scratch marks in the mold where they were compressed further proving that they were pinched in between the two halves of the mold.

5.3.1.2 Micro and Macroscopic Flow and Vacuum Assistance

While not originally intended to be studied the effect of microscopic and macroscopic flow on void creation and processing parameters was quite apparent and is worth discussing. The vacuum also had an effect on the interaction.

This phenomenon actually occurred by accident when the vacuum pump was not turned on until the mold was half filled producing a specimen that was partially filled with voids and partially void free as shown in Figure 5-5. Since the mold was not under vacuum, tiny pockets of air were trapped in between individual fibers, when the resin was injected it was easier for the resin to flow around the fibers (macroscopic flow) rather than push the trapped air out and flow through the fibers as well (microscopic flow). With a lower flow rate the resin would have displaced the air bubbles and saturated the fibers. This proves that applying a vacuum to the mold is very effective at removing trapped air pockets therefore producing better quality specimens and increasing the injection time due to the possibility of a higher injection rate. In Figure 5-5 it is apparent that there is a relatively symmetric pattern of air bubbles; the reason for this is unknown.

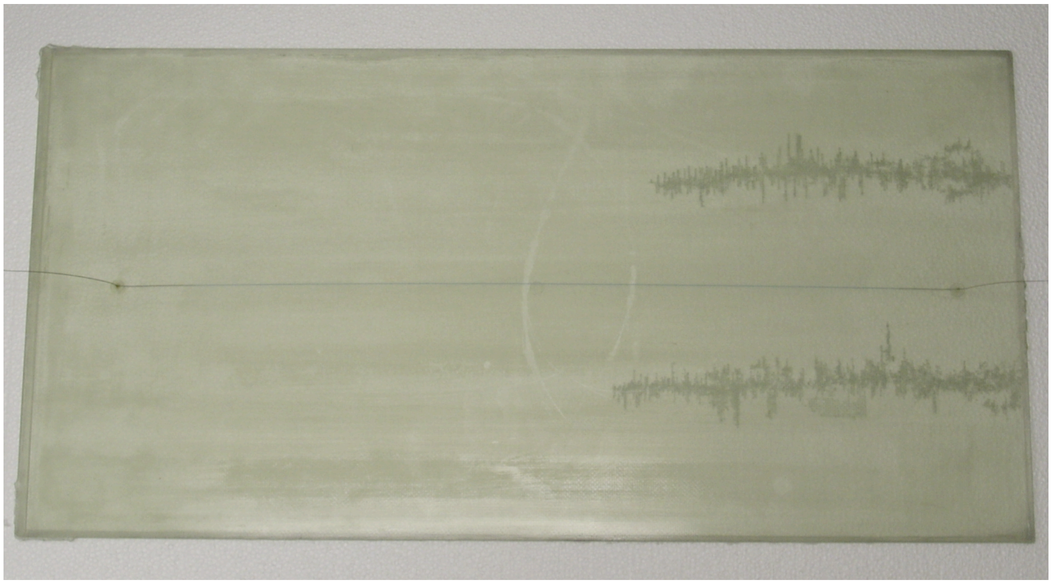

Figure 5-5: Trapped voids due to micro and macroscopic flow

5.3.1.3 Port Locations

The main conclusion that can be made regarding the location of the injection and outlet is that the location of the outlet ports caused a void region in the middle of the mold. This same void was present on every experiment and is partially a result of racetracking along the edges of the mold. Allowing excess resin to pass through the mold allowed the void to travel and eventually exit the mold producing a void free panel. The extra resin that was pumped through the mold to remove this void was wasted. With an optimal location of outlet ports the extra resin required to remove this void and the time it took to inject it could have been conserved therefore making the process more efficient.

The ideal location of the outlet port would have been inline with the current outlet ports, in the middle of the mold rather than in the corners. When the mold was originally designed there was concern that if the outlet port were in that location, the resin would not reach the corners and leave dry spots. This was not the case as racetracking causes the resin to reach the corners before it reaches the middle. While this issue does not affect the final quality of the molded panel, if this was known during the designing stage the molding process could have been made more efficient. This example further strengthens the need for a proper characterization and prediction of racetracking for mold design.

5.3.2 3D Mold

The operating conditions and methods were the same as for the 2-D mold however, the injection pressure was much lower ranging from roughly 0 to 15 psi. A vacuum was also used.

Three, and four layers of 6oz. plain weave E-glass cloth was used as reinforcement and polyurethane foam was used as the core.

5.3.2.1 Racetracking

As anticipated racetracking did not turn out to be as major of an issue compared to the panel. This is in part due to the fact that there are no ‘edges’ in the mold. The fiber is one long sheet that is wrapped around the foam core a number of times, rather than multiple sheets stacked on top of each other as in the panel mold; there are no edges that meet the mold, only surfaces. When loading the mold, the 3D preforms are tightly fitted, compressing the foam slightly ensuring a tight contact with the mold. Because of these two reasons these molds do not suffer from the same issues. Racetracking does however still occur between the mold cavity and the o-ring where the two halves of the mold meet. This is do to the slight gap that is created when the o-ring is compressed and causes the mold to deflect.

5.3.2.2 Saturation

Because the resin is injected through an inlet on the top surface of the component there was concern that dry-spots would form on the bottom surfaces. This problem however, was not encountered. There are three possible reasons why this did not occur. When the preform is fitted into the mold there is small gap between the end of the mold and end of the foam core creating a channel that allows the resin to flow down into the bottom surfaces. Also, after the mold was filled, it was left to sit for five to ten minutes before injecting more resin and allowing it to flow through the mold until air bubbles stoped coming from the mold ensuring the mold is completely saturated. The resin was injected with a very low pressure, therefore low resin velocity inside the mold. This gave the resin enough time to saturate the fibers. The slow resin velocity also avoided any problems with the interaction of micro and macroscopic flow.

5.3.3 Computational Results

An attempt to predict the flow of resin through the mold using commercially available CFD software has been done for all three molds (quasi 2-D panel, foam cored rectangular section and foam cored semicircular section). A more detailed description of the model and mesh are given in Chapter 4. ANSYS ICEM was used to build the mesh and ANSYS 10.0 has been used to model the flow.

In all three cases an attempt to predict the resin flow front has been made. The results are in the form of a flow front prediction. Due to unknown empirical data such as fiber permeability the fill time and resin velocity do not correspond with the experimental data and no attempt was made to do so.

5.3.3.1 Computational Results for Quasi-2D Mold

Presented in Figure 5-6 are screen shots of the mold filling next to contour plots from the CFD simulation. Although during each filling the flow front progresses with a slightly different pattern there is a general flow front shape that is common to each. The variation in flow front pattern among each run is due to racetracking.

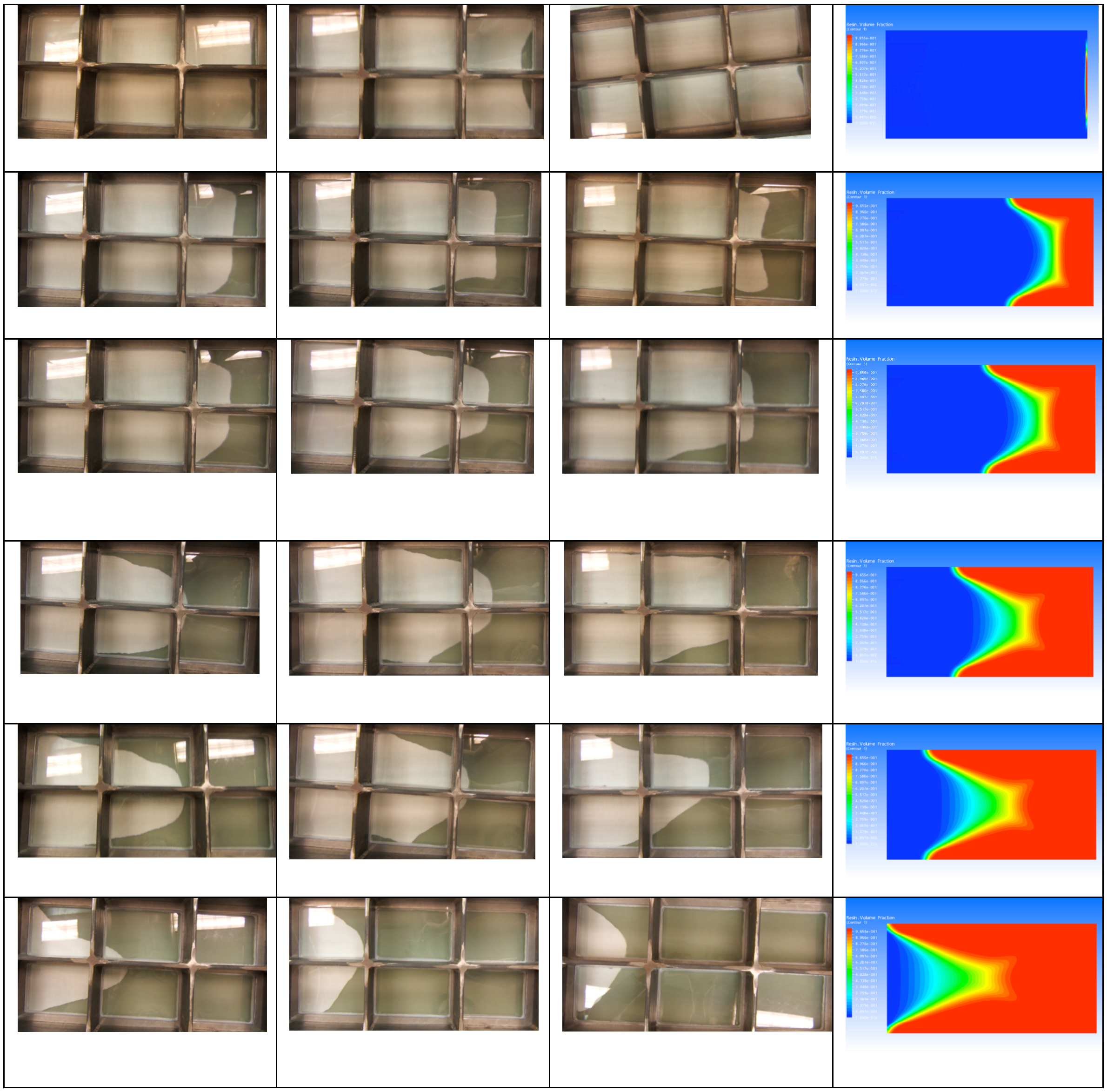

Figure 5-6: Comparison of computational and experimental results for 2D panel

Figure 5-7 shows some examples of severe racetracking. The racetracking in these experiments is due to the manner in which the preform is cut and loaded into the mold. While each preform looks very similar and the method in which they were created and handled was the same, subtle differences had a great effect later on. The final panel in these experiments turned out to be void free because resin was injected through the mold until these voids were removed, however if there was no viewing window then there would be no way to tell if a void was present or how long to continue resin injection to remove this void.

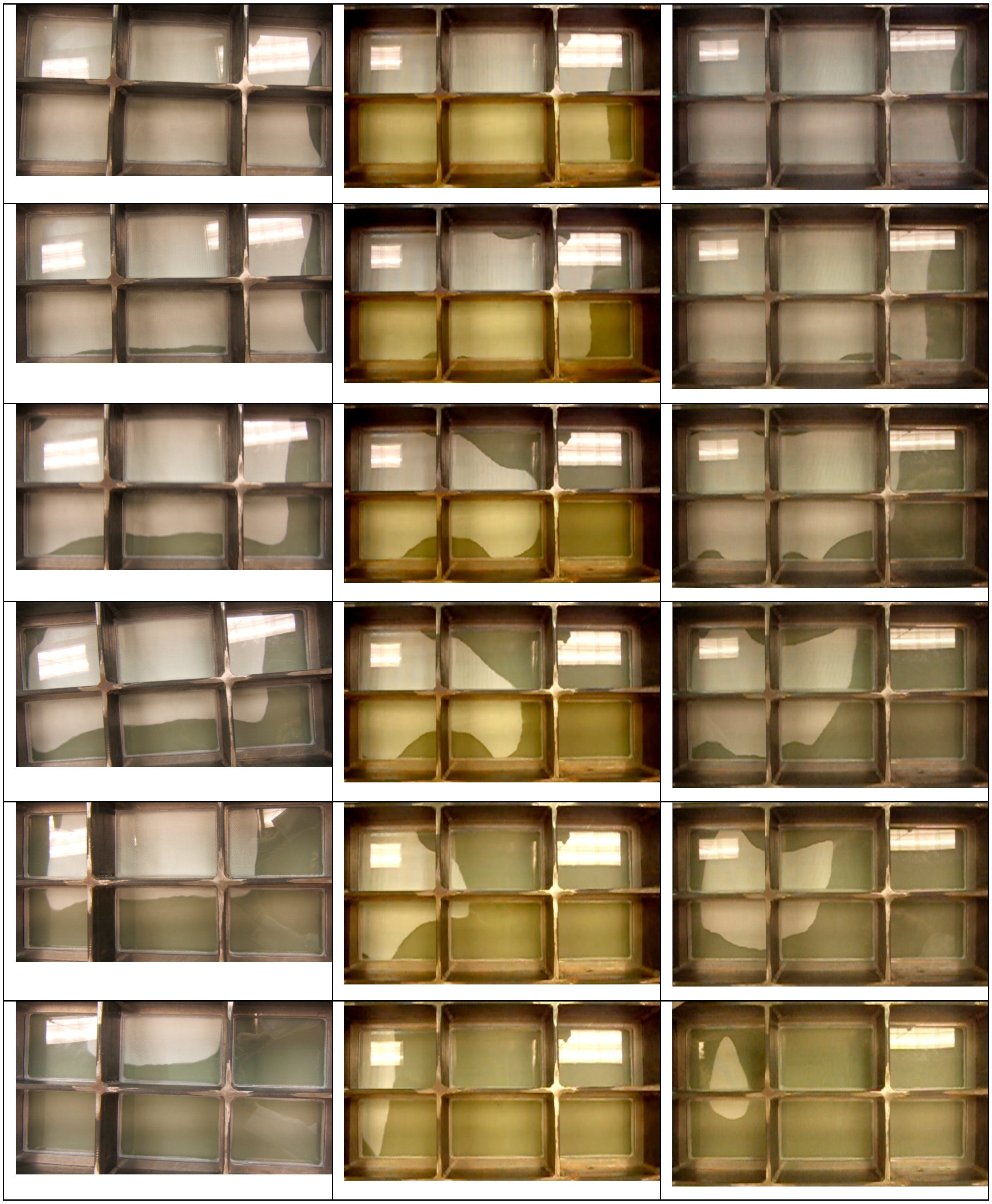

Figure 5-7: Examples of extreme racetracking

5.3.3.2 Comparison of computational results for 3D mold

Presented in Figure 5-8 are images of the rectangular section mold filling next to contour plots from the CFD simulation. The images of the mold filling are taken from above while the contour plots from the simulation are isometric. The racetracking that takes place occurs on the outer edges of the mold where the two mold halves meet rather than inside the mold cavity as in the quasi-2D mold. Since this racetracking was outside of the mold cavity it was not included in the model. This is the main cause of the discrepancy between the model and the experiment.

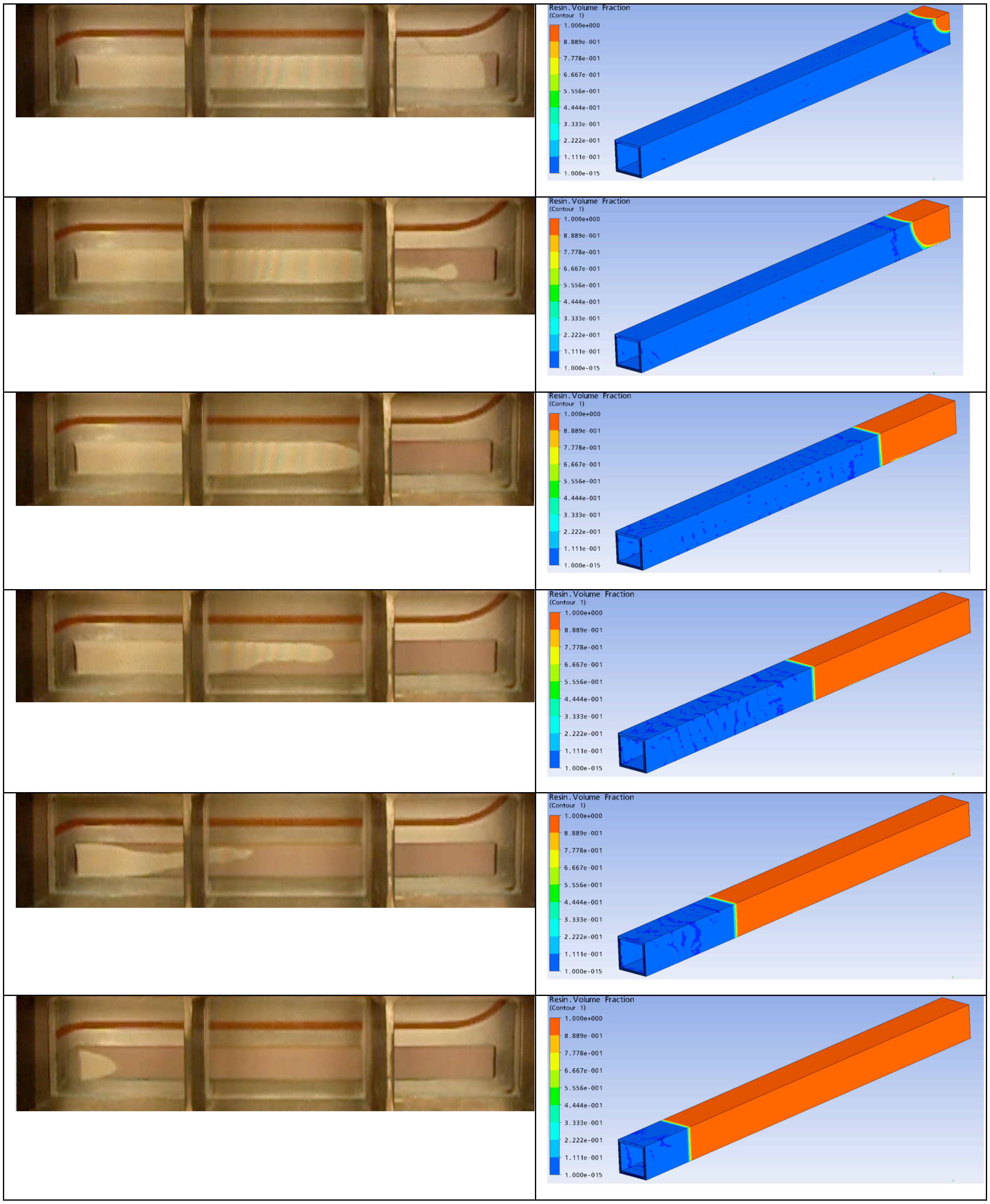

Figure 5-8: Comparison of computational and experimental results for rectangular section

Figure 5-9 shows images of the semicircle section mold filling next to contour plots from the CFD simulation. The images of the mold filling are taken from above while the contour plots from the simulation are isometric. Racetracking occurs in the same manner as with the rectangular mold and is not included in the semicircle mold simulations either. It is the main cause of the discrepancy between the model and the experiment.

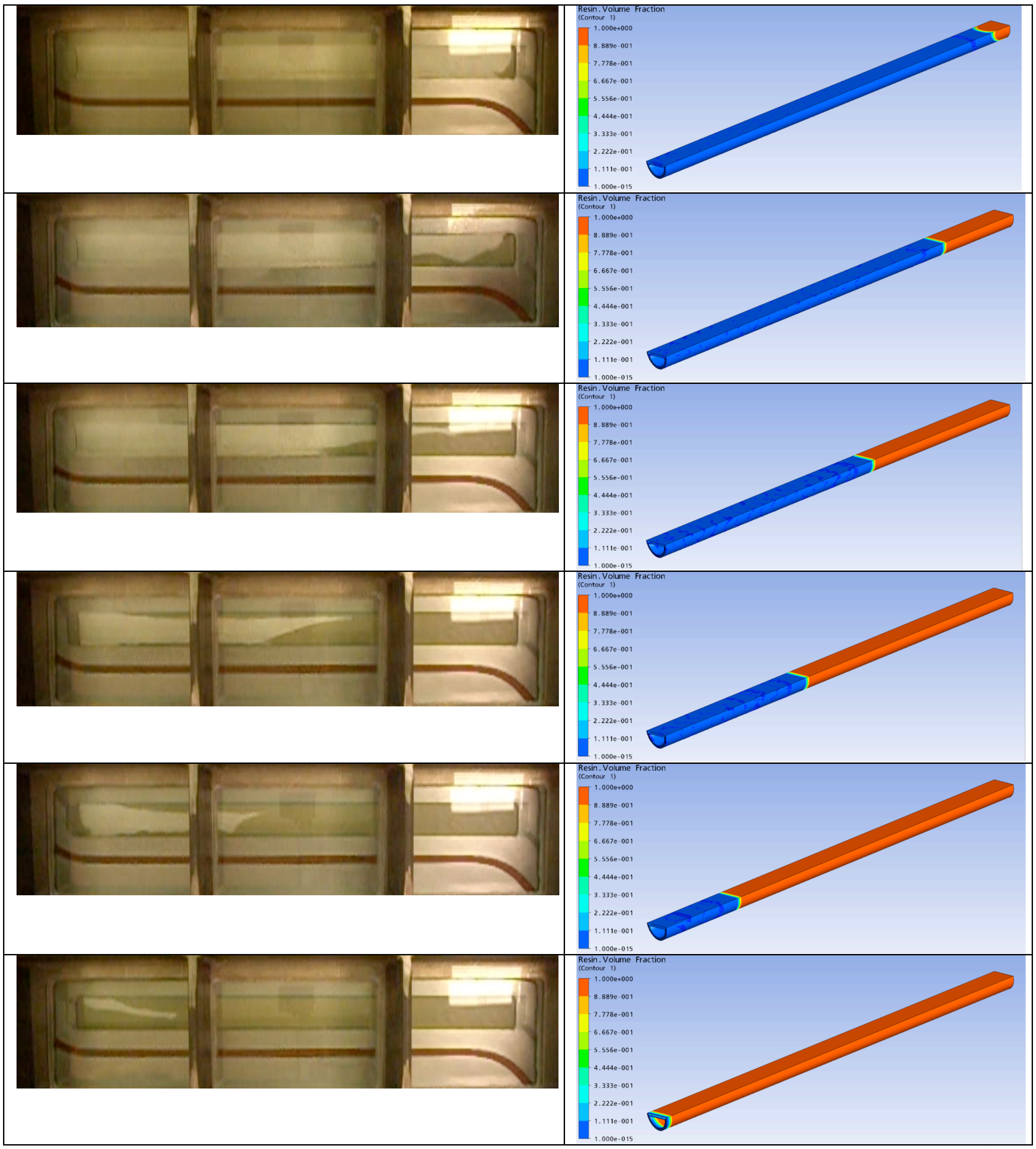

Figure 5-9: Comparison of computational and experimental results for semicircle section

5.4 Conclusions

Composite materials are found everywhere in our daily lives and will be a driving force in the development of technology, especially in the aerospace industry. Resin transfer molding is a promising processing method that has some major advantages over competing methods including the capability of producing complex 3D shapes with a good surface finish, the incorporation of cores and inserts, a tight control over fiber placement and resin volume fraction and the possibility of embedding sensors. Part of the reason RTM has not received widespread use is due to its drawbacks such as its relatively trial and error nature, race tracking, washout, high cycle time and void formation.

In this research program, an entire laboratory (the Advanced Composites Laboratory) was setup from scratch. The lab has the ability of producing quality RTM parts from start to finish including preform construction, molding and post processing. An RTM apparatus with a viewing window to monitor the flow was designed and built. Composite structures with 2-D and 3-D geometries have been manufactured to show the capability of the developed laboratory. The flow of resin through a resin transfer molding machine was studied with specific emphasis on race tracking. A computational model was created to characterize this flow. The flow was modeled using a commercial software suite, ANSYS 10.0 and incorporates racetracking as it occurs in the experimental apparatus. There is good agreement between experimentally observed and numerically computed flow patterns.

The apparatus was designed and built at UVic. It can be separated into seven separate components: the injection system, mold, manipulating/clamping apparatus, catchpot and vacuum system, temperature control system and data acquisition system. The system is modular in the sense that it accepts various mold sizes and shapes. Three mold shapes were molded with this apparatus in completion of this thesis. One quasi-2D panel, a rectangular section with a core and a semicircular section with core were successfully molded.

Some of the challenges faced with developing the apparatus and making it operational include finding a suitable mold release agent, accurately and repeatably producing fiber preforms, finding compatible constituent materials (specifically foam core material) and fine tuning the process to produce void free moldings. These were overcome by both research and trial and error.

A commercial software suite, ANSYS 10.0 was used to model flow through the mold for each shape using CFD methods. The computational models incorporate racetracking as it occurs in the mold and predict the flow front with relative accuracy. The output of this model is in the form of contour plots of the filling process. These are compared to photographs of the actual mold filling.

5.5 Contributions

The main contribution of this work is the development of the Advanced Composites Laboratory from scratch, which can be used for numerous studies and experiments and the development of a computational model to predict the flow of resin through an RTM machine.

The laboratory and equipment is fully functional with the ability to produce composite components with the RTM process. The specific procedure for operating the RTM, including producing the preforms for both quasi-2D and 3D foam cored molds, preparing the mold, removing the molded part and maintaining the mold and associated equipment are contributions to this work.

A number of areas may be researched with this lab. Numerical models of the RTM filling and curing process maybe validated. An optimization based on component geometry, strength, material and the molding process may be performed. The creation of components that contain embedded sensors to study structural health monitoring and used to develop damage detection algorithms is possible. Hybrid composite components can be created and tested to study the interaction of various materials and their effect on performance.

The computational model that predicts flow through the mold may be used to design future molds.

5.6 Recommendations for Future Work

There are a few paths in which future work can be directed. A continuation of the development of the RTM apparatus may be continued. This could involve developing new mold shapes for larger, more complex parts or an entirely new apparatus. There is room for development in the computational model. Parameters such as preform permeability can be measured with the existing apparatus and can be plugged into the model in an attempt to make it more accurate. Experiments may be performed with the apparatus to better characterize the flow. Sensors may be embedded into the mold and used to monitor the filling process, the curing process and the structural health of the molded component while in service. There are applications for this in the aerospace industry and civil engineering industry. This is a very active field of research known as structural health monitoring (SHM).

APPENDIX A RENINFUSION 8601 EPOXY SYSTEM SPEC SHEET

Product Data

RenInfusion™ 8601/Ren® 8601
EPOXY RESIN SYSTEM

DESCRIPTION: RenInfusion 8601(Resin)/Ren 8601(Hardener) is a two-component, low-viscosity epoxy system developed for use in the production of advanced composites using vacuum-assisted resin transfer molding (VARTM), resin transfer molding (RTM), Seemans Composite Resin Injection Molding Process (SCRIMP[SM]), or other infusion processes. The low-mixed viscosity and wet-out potential of RenInfusion 8601/Ren 8601 enhance processability parameters.

RenInfusion 8601/Ren 8601 produces composites with excellent toughness. This product also features elongation at 30% in the neat resin and 11% in the laminate system.

MIX RATIO: By weight: 100 to 25 Resin to Hardener

Mixing Instructions: Measure each component accurately (±5%) into clean containers. Thoroughly mix resin and hardener together (minimum 2 minutes) scraping container sidewalls, bottom, and mixing stick several times to assure a uniform mix.

TYPICAL HANDLING PROPERTIES: Tested @ 77°F(25°C) unless otherwise noted.

Property	Criteria	ASTM Test Method	Test Value
Color	Mixed		Transparent
Viscosity, cP	Resin Hardener Mixed	D-2393	580 25 175
Gel Time, minutes	14 fl.oz.	D-2471	132

NOTE: Typical Properties – These physical properties are reported as typical test values obtained by our test laboratory. If assistance is needed in establishing product specifications, please consult with our Quality Control Department.

RECOMMENDED CURE SCHEDULE:
24 hours @ 77°F (25°C) plus 6 hours @ 150°F (66°C), unless noted otherwise.

NEAT SYSTEM

TYPICAL CURED PROPERTIES: Tested @ 77°F(25°C) unless otherwise noted.

Property	ASTM Test Method	Test[1] Value
Specific Gravity	D-792	1.12
Cubic Inch per Pound	--	24.6
Hardness (Shore D)	D-2240	82
Ultimate Flexural Strength, psi	D-790	8,000
Flexural Modulus, psi	D-790	240,000
Ultimate Tensile Strength, psi	D-638	5,500
Tg by DMA, °F(°C) Cured 6 hours at 200°F(°C)	D-4065	150 (66) 154 (68)
Linear Shrinkage, in/in	D-2566	0.0075
Ultimate Compressive Strength, psi	D-695	9,300
Compressive Modulus, psi	--	214,000
% Elongation	D-638	30
Coefficient of Thermal Expansion, in/in/°F -22° to 86°(-30° to 30°C)	D-3386	4.34×10^{-5}

NOTE: All properties are of neat product form (non-composite).

VARTM PROCESS LAMINATE

TYPICAL CURED PROPERTIES: Tested @ 77°F(25°C) unless otherwise noted.

Property	ASTM Test Method	Test[2] Value
Hardness (Shore D)	D-2240	93
Ultimate Flexural Strength, psi	D-790	81,000
Flexural Modulus, psi	D-790	3,020,000
Ultimate Tensile Strength, psi	D-638	61,500
Ultimate Compressive Strength, psi	D-695	23,200
% Elongation	D-638	11
Coefficient of Thermal Expansion, in/in/°F-22°-86°	D-3386	18.9×10^{-6}

LAY-UP PROCESS:

Panel Type:	Approximately 3 ft. x 2 ft. flat panel
Cloth Type:	2 layers QM 6408 50 glass cloth
Cloth Rotation:	0 degrees
Procedure:	VARTM, flat panel
Laminate Thickness:	3.3 ± 0.1mm
Laminate Resin Content:	27.4%

[1] Cured 24 hours at 77°F (25°C) plus 6 hours at 150°F (66°C), unless noted otherwise.
[2] Cured 24 hours at 77°F (25°C) plus 3 hours at 130°F (54°C), unless noted otherwise.

PACKAGING:

Unit		Weight
5 gallon	*Resin*	36 lb.
2 x gallon package	*Hardener*	9 lb.

STORAGE: Store at 60-100°F in a dry place. After use tightly reseal.

CONDITIONING: Stir well before use. This material will separate.

HANDLING: Work in a well ventilated area and use clean, dry tools for mixing and applying. For two component system, combine the resin and hardener according to mix ratio. Mix together thoroughly and use immediately after mixing. Material temperature should not be below 65°F (18°C) when mixing.

SHELF LIFE: Provided materials are stored under the recommended storage conditions in their original containers, they will remain in useable condition for at least one year from date of shipping.

SAFETY/HANDLING PRECAUTIONS: Do not use or handle this product until the Material Safety Data Sheet has been read and understood.

RenInfusion 8601

DANGER! Causes severe skin irritation. Causes eye irritation. May cause skin burns and allergic skin reaction.
Avoid contact with eyes, skin, or clothing.
Avoid prolonged or repeated contact with skin.
Wash thoroughly after handling.

SAFETY/HANDLING PRECAUTIONS (continued)

Ren 8601

DANGER! CORROSIVE – Causes eye burns and skin burns. Harmful if inhaled, or if absorbed through skin.
Do not get in eyes, on skin, or on clothing.
Avoid breathing vapor or mist.
Keep container closed.
Use with adequate ventilation.
Wash thoroughly after handling.

FIRST AID: In case of contact with:

Skin: Immediately wash with soap and water. Remove contaminated clothing and launder before reuse. Destroy contaminated shoes.
Eyes: Immediately flush with water for at least 15 minutes. Call a physician.
Ingestion: If conscious, give plenty of water to drink. Do not induce vomiting. Call a physician.
Inhalation: Remove to fresh air. Administer oxygen or artificial respiration if necessary. Call a physician.
Other: Referral to physician is recommended if there is any question about the seriousness of any injury.

PRECAUTIONARY NOTE: Thermosetting systems generate heat when curing. The amount of heat and the period of time in which heat is released vary significantly between systems. Additionally, ambient or compound temperature, amount of material mixed, and construction and shape of the mold or container can also be factors in the temperature profile of a mixed system. In some cases, the thermosetting reaction can be vigorous, generating heat sufficient to cause decomposition of the system with subsequent liberation of large volumes of acrid smoke.

A good rule of thumb is never mix more material than can be applied during the stated pot life or gel time. Also take care when using materials in applications other than stated on the Product Data Sheet, i.e., a laminating resin for casting.

Please feel welcome to call our Product Information Department or your local Ren representative for instructions before you start your job.

IMPORTANT: The following supersedes Buyer's documents. SELLER MAKES NO REPRESENTATION OR WARRANTY, EXPRESS OR IMPLIED, INCLUDING WARRANTIES AND CONDITIONS OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE. No statements herein are to be construed as inducements to infringe any relevant patent. Under no circumstances shall Seller be liable for incidental, consequential, or indirect damages for alleged negligence, breach of warranty, strict liability, tort, or contract arising in connection with the product(s). Buyer's sole remedy and Seller's sole liability for any claims shall be Buyer's purchase price. Data and results are based on controlled or lab work and must be confirmed by Buyer by testing for its intended conditions of use. The product(s) has not been tested for, and is therefore not recommended for, uses for which prolonged contact with mucous membranes, abraded skin, or blood is intended; or for uses for which implantation within the human body is intended.

Distributed by: FREEMAN MFG & SUPPLY CO. 1101 MOORE RD / AVON, OH 44011
800-321-8511 www.freemansupply.com

REFERENCES

[1] Mel M. Schwartz, Composite Materials, Volume 2: Processing, Fabrication and Applications. Prentice Hall, Upper Saddle River, New Jersey, 1997

[2] The research requirements of the transport sectors to facilitate an increased usage of composite materials, Prepared by EADS Detuschland GmbH, Corporate Research Centre, June 2004, Part I: The Composite Material Research Requirements of the Aerospace Industry

[3] http://en.wikipedia.org/wiki/Composite_materials

[4] Potter, K.D., *The early history of resin transfer moulding process for aerospace applications.* Composites: Part A 30 (1999), 619-621.

[5] Scott Robert John Bumpus, 2005, Tensile and Flexure Testing of an Optimization Capable Advanced Composite Material, MASc Thesis, University of Victoria, Canada

[6] www.gurit .com

[7] ASM Handbook, Volume 21: Composites, December 2001

[8] Mel M. Schwartz, Composite Materials, Volume 1: Properties, Nondestructive Testing and Repair. Prentice Hall, Upper Saddle River, New Jersey, 1997

[9] http://ceramics.staging.10floor.com/news/ceramic_tech_today/ct2007/20070905carbon_fiber.aspx

[10] Shojaei, S.R. Ghaffarian and S.M.H. Karimian, 'Modeling and Simulation Approaches in the Resin Transfer Molding Process: A Review', *Polymer Composites*, Vol. 24, No. 4, pp. 525-544, 2003

[11] Abbassi, A. and Shahnazari, M.R., "Numerical Modeling of Mold Filling and Curing in Non-isothermal RTM Process", *Applied Thermal Engineering*, 24, pp. 2453-2465, 2004

[12] Shojaei, A., Ghaffarian, S.R. and Karimian, S.M.H., , 'Modeling and Simulation Approaches in the Resin Transfer Molding Process: A Review', *Polymer Composites*, Vol. 24, No. 4, pp. 525-544, 2003

[13] Shojaei, A., Ghaffarian, S.R. and Karimian, S.M.H., " Simulation of the Three-Dimensional Non-isothermal Mold Filling Process in Resin Transfer Molding", *Composites Science and Technology,* 63, pp. 1931-1948, 2003

[14] Henz, B.J., Tamma, K.K., Mohan, R.V., Ngo, N.D., "Process Modelling of Composites by Resin Transfer Molding: Sensitivity Analysis for Non-Isothermal Considerations", *International Journal of Numerical Methods for Heat & Fluid Flow*, Vol. 15 No. 7, pp. 631-653, 2005

[15] ANSYS CFX-Solver, Release 10.0: Theory, ANSYS Europe, Ltd., 2005.

[16] ANSYS CFX-Modeling, Release 10.0: Theory, ANSYS Europe, Ltd., 2005.

[17] Hammami, A., Gauvin, R., Trochu, F., "Modeling the Edge Effect in Liquid Composites Molding", *Composites Part A, Applied Science and Manufacturing*, pp. 603-609, 1998.

[18] Henne, M., Ermanni, P., Deleglise, M., Krawczak, P., " Heat Transfer of Fibre Beds in Resin Transfer Moulding: An Experimental Approach", *Composites Science and Technology*, 64, pp.1191-1202, 2004.

[19] C. W. Hirt and B. D. Nichols, 'Volume of fluid (VOF) methods for the dynamics of free boundaries', J. Comput. Phys., 39, 201–225 (1981).

[20] Gebart, B.R., "Permeability of Unidirectional Reinforcements for RTM", *Journal of Composite Materials,* Vol. 26, No. 8, pp.1100-1133, 1992.

[21] Yoo, Y. and Lee, W., I., 'Numerical Simulation of the Resin Transfer Mold Filling Process Using the Boundary Element Method', *Polymer Composites,* Vol. 17, No. 3, pp 368-374, 1996.

[22] Comas-Cardona, S., Greoenenboom, P., Binetruy, C., Krawczak, P., "A Generic Mixed FE-SPH Method to Address Hydro-Mechanical Coupling in Liquid Moulding Processes", *Composites Part A, Applied Science and Manufacturing*, 36, pp. 1004-1010, 2005.

[23] Kiuna, N., Lawrence, C.J., Fontana, Q.P.V., Lee, P.D., Selerland, T., Spelt, P.D.M., "A model for resin viscosity during cure in the resin transfer molding process", *Composites Part A, Applied Science and Manufacturing*, 33, pp. 1497-1503, 2002

[24] Wang, Bai-Chen; Huang, Yu-Dong; Liu, Li, "Numerical analysis on microscopic flow behavior of resin with resin transfer molding (RTM) process", *Journal of Solid Rocket Technology,* Vol. 29, No. 4, pp. 297-300, 2006

[25] Binetruy, C.; Hilaire, B.; Pabiot, J., **"**Interactions between flows occurring inside and outside fabric tows during RTM**",** *Composites Science and Technology*, Vol. 57, No. 5, pp. 587-596, 1997

[26] Lombardi, A. V., "Technological optimisation of a smart thermosetting aeronautical composite subject to fatigue bending loads", *Progress in Aerospace Sciences*, Vol. 39, pp. 385–404, 2003

[27] Ruiz, E., Trochu, F., "Thermomechanical properties during cure of glass-polyester RTM composites: elastic and viscoelastic modelling", *Journal of Composite Materials,* Vol. 39, No. 10, pp. 881-916, 2005

[28] N. Pantelelis, T. Vrouvakis, K. Spentzas , "Cure cycle design for composite materials using computer simulation and optimisation tools", Forschung im Ingenieurwesen (Springer-Verlag), Vol. 67, pp. 254-262, 2003

[29] V. Rohatgi, N. Patel, L. James, "Experimental Investigation of Flow-Induced Microvoids During Impregnation of Unidirectional Stitched Fiberglass Mat", *Polymer Composites*, Vol. 17, No. 2, pp. 161-170, 1996

[30] Rudman, M., "Volume-Tracking Methods for Interfacial Flow Calculations", *International Journal for Numerical Methods in Fluids*, Vol. 24, pp. 671-691, 1997.

[31] Bickerton, S., Stadtfeld, H.C., Steiner, K.V., Advani, S.G., "Design and Application of Actively Controlled Injection Schemes for Resin-Transfer Molding", *Composites Science and Technology*, 61, pp.1625-1637, 2001.

[32] Andersson, H.M., Lundstrom, T.S., Langhans, N., "Computational Fluid Dynamics Applied to the Vacuum Infusion Process", *Polymer Composites,* pp. 231-239, 2005.

[33] Bickerton, S., Advani, G., "Experimental Analysis and Numerical Modeling of Flow Channel Effects in Resin Transfer Molding", *Polymer Composites,* Vol. 21, No.1, pp. 134-153, 2002.

[34] Anderson, H.M., Lundstrom, T.S., Gebart, B.R., "Numerical Model for Vacuum Infusion Manufacturing of Polymer Composites", *International Journal of Numerical Methods for Heat & Fluid Flow*, Vol. 13, No. 3, pp. 383-394, 2003.

[35] Ferland, P., Guittard, D., Trochu, F., "Concurrent Methods for Permeability Measurement in Resin Transfer Molding", *Polymer Composites,* Vol. 17, No. 1, pp 149-158, 1996.

[36] J.H. Ferziger & M. Peric, *Computational Methods for Fluid Dynamics*, Springer, 1996

[37] Advani, Suresh G., Sozer, E. Murat, *Process Modelling in Composites Manufacturing*, Marcel Dekker, Inc., New York, 2003